Heating Strategies in a Renewable Energy Transition

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HEATING STRATEGIES IN A RENEWABLE ENERGY TRANSITION

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SUMMARY

Introduction: The generation of renewable energy (RE) is an increasingly relevant topic in many countries for a multitude of reasons, and the challenges related to its integration into existing energy systems are becoming more and more evident. In Europe, heating demand makes up about one third of the total final energy demand, equivalent to the share for electricity. However, heating has received much less focus when it comes to the development of RE solutions than electricity. Particularly for cities, there are unresolved questions about how the heating demand can be covered in a feasible way in the future. In Denmark, the introduction of RE has been ongoing for several decades, and district heating (DH) systems have been contributing to the flexibility of the country's electricity production via combined heat and power (CHP) and thermal storage. However, this beneficial synergy is now declining because CHP production is being replaced with wind power.

The 4^{th} generation of DH (4DH) is a concept that describes how DH and cooling should develop in the future to be able to adapt to changing conditions in the transition towards 100% RE systems. The purpose of 4DH is to identify future challenges and solutions for reaching a 100% RE system. The concept includes the integration of the heating sector into the overall energy system and is seen as an integral part of smart energy systems. Smart energy systems is an analytical approach, which is applied in the analyses of this thesis.

Purpose: The purpose of this thesis is to contribute to the solution of how DH should be developed in the transition towards a 100% RE system to meet societal goals of low socioeconomic costs and a sustainable use of resources. This is done through analyses of different issues related to the future of DH. The thesis is structured around three main areas;

1) New heat sources,
2) Reductions in heat demands and
3) Changes in the supply system

Theory and Methods: The main approach to the research presented in this thesis is to develop different alternative scenarios for strategies within DH that address some of the central issues involved in the transition towards a smart energy system based on 100% RE. This is done using the theoretical framework of Choice Awareness, which allows one to frame the development of energy systems into a context of policy development. Here, some solutions that are feasible to society might be eliminated from the public decision making process due to powerful stakeholders' own interests. Socioeconomic feasibility studies are performed, mainly using the EnergyPLAN tool for modelling and simulation, with the main assessment parameters being socioeconomic costs and total primary energy supply.

New heat sources: A number of new heat sources will be relevant for DH supply in the future, as fossil fuels are phased out and the production of heat from CHP plants decreases. In a 100% RE system, CHP plants should be highly flexible to accommodate for fluctuations in the RE supply. Heat pumps (HPs), industrial excess heat, solar- and geothermal energy will replace the reduced production from conventional sources (CHP, boilers and waste incineration). HPs, in particular, are a central technology in this context, which can enable the utilisation of new low-temperature heat sources. Through the analyses, it has been shown that there are available heat sources for HPs in all parts of the country, but the geographical distribution of the heat source volume is not proportional to the heat demands. These heat sources include waste water, excess heat from supermarkets, ground and drinking water and ambient temperature sources.

Reductions in heat demands: Reductions in heat demands is one of the key issues for the heating sector in the transition towards 100% RE. Savings in space heating, ranging from 30-50% of current demand, have previously been shown to reduce total energy system costs and primary energy consumption; but, equally important are the savings in investment costs for production capacity. This conclusion applies for individual heating as well as for DH. In connection to this thesis, it has been found that reductions in heat losses from DH grids, from 30-45%, through investment in better insulated pipes, are feasible from a socioeconomic perspective.

Changes in the supply system: Changes in the supply systems must happen in two different but closely connected areas: 1) integration of the energy sectors and 2) the heat distribution systems. Generally, these changes have two central purposes: to improve the efficiency and increase the flexibility of the supply system. Regarding integration of the production system, electric HPs have a central role to play. They consume electricity and produce DH using a low temperature heat source, which improves the integration of the electricity and heating sectors, and thereby both the flexibility and efficiency of the overall energy system. An assessment of the potential for integrating HPs into the Danish energy system shows that a capacity of between 450 and 900 MW_e will be feasible already in 2020, which is equivalent to 10-15% of the planned wind power capacity. Such capacity would reduce fuel consumption by 5 to 7 TWh/year in Denmark, which is about 6-8% of the fuel consumption for heat and power production in that system. In the distribution systems, efficiency can be significantly increased by improving pipe insulation and lowering DH system temperatures. In a comparison of different alternative DH concepts with a focus on temperature level, increased HP efficiency is shown to provide a central benefit in reducing the DH temperature level. The study concludes that the DH temperature set should be reduced as much as possible, until reaching the point at which the domestic hot water temperature must be boosted locally in buildings using electricity, because that would require investments that are greater than savings, both in terms of costs and primary energy supply.

DANSK RESUMÉ

Indledning: Produktion af vedvarende energi (VE) er et emne med voksende relevans i mange lande af en række forskellige grunde og udfordringerne i forbindelse med dets integration i eksisterende energisystemer bliver mere og mere tydelige. I Europa udgør varmebehov en tredjedel af det totale slutforbrug af energi, svarende til andelen for elektricitet. Varmebehov har dog fået meget mindre fokus i forbindelse med udvikling af VE-løsninger end el-sektoren. Specielt i byer er der ubesvarede spørgsmål om hvordan varmebehov kan dækkes på en effektiv og samfundsmæssig forsvarlig måde i fremtiden. Indpasningen af VE har i Danmark været igang i flere årtier, og fjernvarmen har her bidraget til fleksibilitet til elproduktionen via kraftvarme og varmelagring. Denne synergi er dog nu aftagende, fordi kraftvarme erstattes af vindkraft.

4. generation af fjernvarme (4DH) er et koncept som beskriver hvordan fjernvarme og –køling bør udvikles fremadrettet for at være tilpasset de nye betingelser i omstillingen mod mere VE. Formålet med 4DH er at identificere kommende udfordringer og løsninger for at nå et 100 % VE system. Konceptet inkluderer integrationen af varmesektoren in det overordnede energysystem og det ses som en del af intelligente energisystemer. Intelligente energisystemer er en analytisk tilgang, som anvendes i analyserne i denne afhandling.

Formål: Formålet med denne afhandling er, at bidrage til løsningen på hvordan fjernvarmen bør udvikles i omstillingen mod et 100 % VE-system for at imødekomme samfundsmæssige målsætninger om lave omkostninger og et bæredygtigt forbrug af ressourcer. Dette gøres gennem analyser af forskellige forhold relateret til fjernvarme i fremtiden. Denne afhandling er struktureret omkring tre hovedområder:

1) Nye varmekilder,
2) Reduktioner i varmebehov og
3) Forandringer i forsyningssystemet

Teori og metoder: Den overordnede tilgang anvendt i forskningen præsenteret i denne afhandling er at opstille forskellige alternative strategier indenfor fjernvarme som adresserer nogle af de centrale forhold i omstillingen til intelligente energisystemer baseret på 100 % VE. Hertil er Choice Awareness-teorien anvendt som forståelsesramme, hvilket muliggør en perspektivering af udviklingen i energisystemerne i sammenhæng med den politiske udvikling. Samfundsøkonomiske analyser er gennemført, primært ved brug af værktøjet EnergyPLAN til modellering og simulering, med samfundsøkonomiske omkostninger og endeligt energiforbrug som primære parametre i sammenligningen af alternativer.

Nye varmekilder: Flere nye varmekilder vil blive relevante for fjernvarmeforsyning i fremtiden når fossile brændsler udfases og produktionen fra kraftvarmeværker falder. I et 100 % VE-system bør kraftvarmeværker være meget fleksible i deres produktion for at bidrage til indpasningen af fluktuerende VE-kilder i forsyningen. Varmepumper (VP), industriel overskudsvarme, solvarme og geotermi vil erstatte den faldende produktion fra brændselsbaserede kilder. Specielt VP'er er en central teknologi, da de kan bidrage til udnyttelse af lav-temperatur varmekilder. Gennem dette studie er det sandsynliggjort at der findes varmekilder til varmepumper ovaralt i Danmark, dog er fordelingen af kilderne ikke proportional med varmebehovet. Disse varmekilder inkluderer spildevand, overskudsvarme fra supermarkeder, grund- og drikkevand og kilder til omgivelsesvarme.

Reduktioner i varmebehov: Reduktioner i varmebehov er en af hjørnestenene i en effektiv omstilling af varmesektoren mod 100 % VE. Besparelser i rumvarme svarende til 30-50 % af det nuværende behov er tidligere vist, at kunne reducere de totale systemomkostninger og endelige energiforbrug; men lige så vigtig er de medfølgende muligheder for at reducere investeringerne i spoduktionskapacitet. Dette gør sig gældende for både individuel opvarmning og fjernvarme. I forbindelse med denne afhandlig er det også fundet samfundsøkonomisk rentabelt at reducere tab fra fjernvarmerør med mellem 30 og 45 %, ved anvendelse af bedre isolerede rør.

Forandringer i forsyningssystemet: Der skal implementeres forandringer i to forskellige dele af forsyningssystemerne: 1) integration af energisektorerne og 2) varmeforsyningssystemerne. Generelt set er der to formål med disse forandringer; at forbedre effektiviteten og øge fleksibiliteten i forsyningen. I forhold til integration af energisektorerne har VP'er en central rolle. De forbruger el til produktion af varme ved at udnytte en lav-temperaturvarmekilde, hvilket øger både fleksibiliteten og effektiviteten af det totale system. En vurdering af potentialet for at integrere VP'er i det danske energisystem viser at en kapacitet på mellem 450 og 900 MW_e er rentabel allerede i 2020, hvilket svarer til 10-15% af den planlagte vindkraftkapacitet. En sådan kapacitet vil samtidig kunne reducere forbruget af brændsel med 5 til 7 TWh/år i Danmark, svarende til 6-8 % af brændselsforbruget til el- og varmeproduktion. I varmeforsyningssystemerne kan effektiviteten markant øges ved at forbedre rørisolering og reducere systemtemperaturerne. En sammenligning af forskellige fjernvarmekoncepter med fokus på systemernes temperaturniveau, viser at øget virkningsgrad på fjernvarme VP'er er en af de væsentligste fordele ved reduceret temperaturniveau. Det konkluderes i studiet at temperaturerne bør sænkes så meget som muligt uden at lokal hævning af temperatur med el er nødvendig, for det vil kræve øgede investeringer i bygninger og forsyningssystem, som overstiger de besparelserne ved den øgede effektivitet, både i forhold til samfundsøkonomiske omkostninger og brændselsforbrug.

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My colleagues in the Research Group of Sustainable Energy Planning have been a great support. Both on a professional level, as everyone have been willing to help and discuss my research with me, but also for creating a great work place, with chats and laughs during coffee breaks, cake club, Friday beers, Christmas lunches and field trips around the Energy-World.

I have had the opportunity and pleasure of working with many people on my research from different universities and institutes. Particularly, I would like to thank the co-authors of the papers on which this thesis is based. I have learned much from their cooperation, and they have contributed very much to the development of the content presented in this thesis.

I would also like to thank The Division of Energy Systems at Linköping University for hosting me during my external stay. I learned a lot about energy systems modelling, but also about different ways of viewing an energy system and its context. Especially, I would like to thank Louise Trygg, who made it possible and arranged everything around my visit to their research group.

Finally, I would like to thank my family, and especially my girlfriend Anne, for supporting me and for bearing with me, when I have been talking too much about district heating and wind turbines.

LIST OF PAPERS

[1] Lund R, Ilic DD, Trygg L. Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark. J Clean Prod 2016;139:219–29. doi:10.1016/j.jclepro.2016.07.135.

[2] Lund R, Mathiesen BV. Large combined heat and power plants in sustainable energy systems. Appl Energy 2015;142:389–95. doi:10.1016/j.apenergy.2015.01.013.

[3] Lund R, Persson U. Mapping of potential heat sources for heat pumps for district heating in Denmark. Energy 2016;110:129–38. doi:10.1016/j.energy.2015.12.127.

[4] Lund R, Mohammadi S. Choice of insulation standard for pipe networks in 4th generation district heating systems. Appl Therm Eng 2016;98:256–64. doi:10.1016/j.applthermaleng.2015.12.015.

[5] Lund R, Dominkovic D, Mathiesen BV. Socioeconomic Consequences of Short-Term Decisions on Large Heat Pumps and Biomass Consumption for Heat Strategies in Denmark. 11th Conf. Sustain. Dev. Energy, Water Environ. Syst. – SDEWES Conf., Lisbon, Portugal: 2016.

[6] Lund R, Østergaard DS, Yang X, Mathiesen BV. Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective. Int J Sustain Energy Plan Manag 2017;12:5–18. doi:10.5278/ijsepm.2017.12.2.

The above listed papers [1–6], are the papers upon which this PhD thesis is based. The papers are the first six entries in the bibliography, and the numbering throughout the thesis refers to this. For example *Paper 1* refers to [1].

ABREVIATIONS

4DH	Fourth generation district heating
APF	Advanced pulverised fuel (CHP/power plant)
CCGT	Combined cycle gas turbine
CEESA	Coherent Energy and Environmental System Analysis
CFB	Circulating fluidised bed (CHP plant)
CHP	Combined heat and power
COP	Coefficient of performance
DEA	Danish Energy Agency
DH	District heating
DHC	District heating and cooling
DHW	Domestic hot water
GIS	Geographic information system
HP	Heat pump
HRE	Heat Roadmap Europe
IDA	Danish Association of Engineers
LTDH	Low temperature district heating
RE	Renewable energy
SH	Space heating
TES	Thermal energy storage
TSO	Transmission system operator
UNFCCC	United Nations Framework Convention on Climate Change
WEC	World Economic Council

CHAPTER 1. INTRODUCTION

1.1. DEVELOPMENT TOWARDS 100% RENEWABLE ENERGY

On the global level, there is an increasing focus on the introduction of renewable energy (RE), and a variety of strategies are taking form in all parts of the world. The effects of climate change are starting to show, and a consensus among world leaders that climate change is a result of human activity is emerging, as seen at the 21st conference of parties under the UNFCCC in Paris [7]. Air pollution is becoming an increasing problem in the world's largest cities due to the combustion of fuels for transport, electricity and heating [8]. High environmental risks in connection with oil and gas extraction and the safety of coal mining, nuclear plant operation and long-term storage of waste are also significant concerns. At the same time, developments in RE technology have led to large reductions in costs, meaning that RE is becoming economically competitive with conventional technologies [9].

Energy consumption for heating represents about one third of the total final energy consumption in Europe; as such, heating is a very important, and often overlooked, sector to provide with a sustainable supply of energy. Figure 1 shows the division of final energy consumption in the EU. As seen, heating comprises a larger share than electricity consumption, and is greater than the process and transport demands put together. The share of RE in electricity in the EU is already 28%, and the supply from solar, wind and bio has increased from 130 to 520 TWh between 2004 and 2014. An additional 400 TWh of hydro has remained constant over this period [10]. In contrast, the share of RE in the heating sector is only about 10% [11], even though technologies exist today that could provide 100% RE for heating [12].

1.1.1. CONVERSION OF THE HEATING SECTOR TO RENEWABLE ENERGY

Of the heating demands in the EU today, 47% are covered using individual natural gas boilers. In addition, direct electric heating and DH cover 12% each, with natural gas also plays a role in supplying fuel to these facilities [11]. With a total consumption of natural gas in the EU that is three times greater than its production [13,14], there is a high dependence on imported natural gas from Russia and Middle Eastern states, which has proven on multiple occasions to be a problem for the security of supply [15,16].

The Heat Roadmap Europe (HRE) 2 study analyses different strategies for developing a sustainable long term heating supply in the EU. Here, a reduction in total heating demand of between 30-50% is mentioned as a first priority for all countries, regardless of their current heat supply, to reduce energy consumption and to reduce the capacity needs for supplying heat. Secondly, DH should be expanded to cover approximately 50% of the remaining heat demand and individual HPs should be implemented to cover the other 50%. This strategy both improves the system's ability to integrate fluctuating RE and reduces the total energy system costs [17].

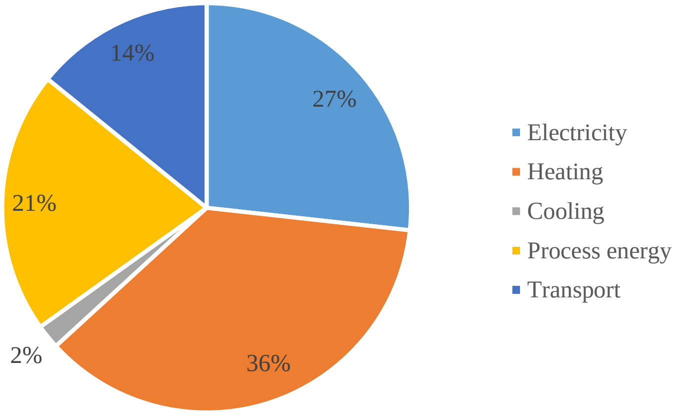

Figure 1: Division of final energy consumption in the EU 2010/2012. Electricity consumption includes some industrial processes, which is subtracted from the Process energy category. [11,18–20] It is assumed that the final energy consumption for transport is one third of the total energy input for transport.

Heating options outside the range of DH systems are less complicated, because each supply unit produces heat for only one consumer and is adjusted accordingly. By contrast, DH systems are much larger and are dependent on many consumers and, sometimes, many producers as well. The DH infrastructure can also, for the most part, be maintained while replacing the supply units and heat sources. DH systems can also operate across more energy systems at the same time, such as electricity, cooling, gas and waste incineration, where individual heating systems typically only operate on one external energy market, e.g. electricity or gas. This means that many more combinations of components and systems can offer relevant solutions within a DH system. A number of studies suggest HPs as a feasible solution in a 100% RE system [17,21–23]. In [22], different alternatives are assessed for individual heating solutions, including biomass boilers, HPs, electric heating (EH) and micro-CHP, all of which is considered in combination with solar thermal. This showed that EH is slightly less costly than HPs, but uses significantly more fuel, and HPs are therefore the recommended solutions for heating in individual buildings.

Moreover, the population of Europe – and the rest of the world – is expected to increase, and is increasingly moving to cities. Today, 54% of the World's population live in urban areas, which is expected to grow to 66% in 2050; Asia, especially, is expected to experience a steep increase in urban population. The population in Europe living in cities today is 73% and is expected to grow to exceed 80% in 2050. This means that the potential of DH systems will continue to grow in the future. [24]

In this thesis, the focus is on the role of DH, and specifically on the challenges and potentials of its implementation within the context of the transition towards 100% RE supply.

1.1.2. CHANGING CONDITIONS FOR DISTRICT HEATING

The external conditions for DH systems are currently changing, which is forcing many DH companies to change the way the way they operate. Some of the main changes in conditions are listed below:

- Increasing share of fluctuating renewable electricity
- Low marginal electricity prices
- Political wish to reduce CO_2-emissions
- Decreasing heat demands

RE is continuously increasing its share in the energy supply, and particularly wind power has established a significant role in the Nordic countries. The large production of wind power reduces prices on the Nordic electricity market due to the structure of the current bidding and pricing scheme. At the same time, there is a wish in both local and national governments to reduce CO_2-emissions. There is also an increasing focus on energy savings in buildings, which will reduce the demands for DH; but, on the other hand, the total number of DH consumers is increasing, which indicates that the linear heat density is decreasing, which may influence the general feasibility of DH. There are many uncertain parameters for DH companies and governments to consider. It is important that a proper framework is established to ensure that DH companies and local governments pursue a socioeconomically feasible development of energy supply systems. This framework should also induce development that complies with the long-term goals of avoiding unnecessary investments in the supply systems.

1.1.3. THE FOURTH GENERATION OF DISTRICT HEATING

The fourth generation of DH (4DH) is a concept defined as a point of reference for how district heating and cooling (DHC) should develop in the future to be able to adapt to the changing conditions in the transition towards RE systems. The purpose of this is to identify future challenges and solutions for reaching a RE system. The concept includes the integration of the heating sector into the overall energy system and the development of smart energy systems, which is presented in more detail in Section 2.2 [25].

The development of DH technology and systems, from the first up to the fourth generation, is defined by decreasing supply temperature levels, improved efficiency of supply pipe networks, increasing amounts of RE and increasing integration with the other energy sectors (see Figure 2). The third generation is similar to the current commonly installed DH system in Denmark, whereas the fourth generation is still in a research, development and demonstration process.

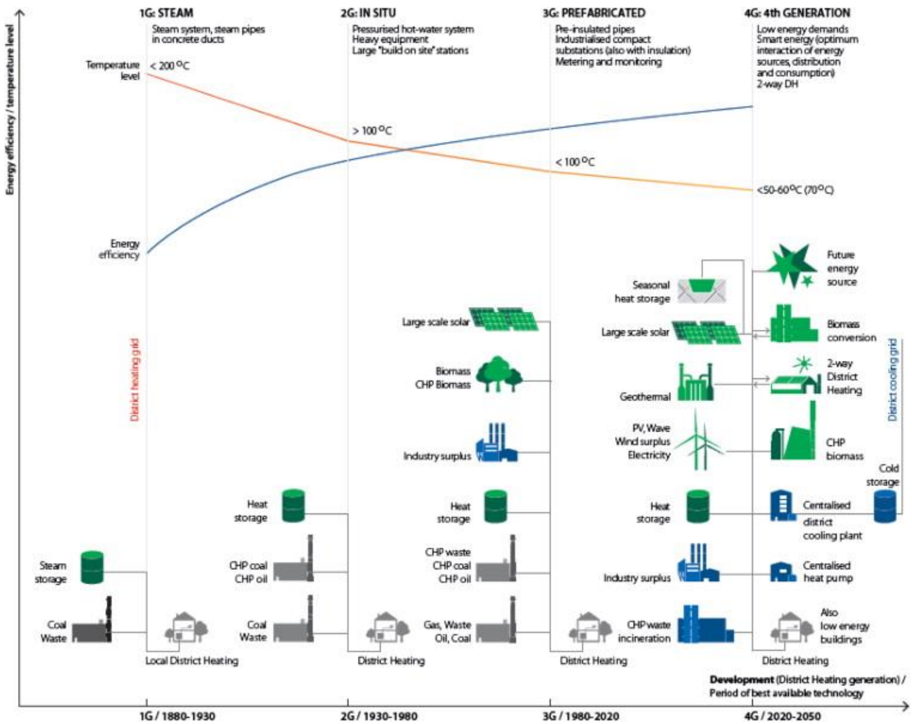

Figure 2: Illustration of the concept of 4th Generation District Heating in comparison to the previous three generations. Figure from [25].

Lund et al. [25] categorises the challenges involved in the development of DH from 1st to 4th generation into three categories:

1) Demand and distribution
2) Production and system integration
3) Planning and implementation

These three categories reflect the need for interventions on three different levels, where different approaches and solutions are needed. The demand and distribution category contains the technical issues in the building and pipe networks. Production and system integration relates to the supply of DH, which sources are included and how they are included in the system. The category of planning and implementation contains structural and regulatory challenges and the purpose of these are to remove barriers and create incentives to implement the best and most feasible solution with a long-term perspective. In many cases, solutions within the last category are prerequisites for the realisation of solutions to challenges in the first two categories. For example, it is necessary to create an incentive for reducing space heating in buildings before large scale investments in building insulation can be expected.

1.1.4. THE CASE OF DENMARK

In Denmark electricity and heat production have been coupled for several decades through the coproduction of electricity and heat by a large number of combined heat and power (CHP) plants all over the country for use within widespread DH systems [26]. The CHP plants were constructed to improve the energy efficiency of heat and power production. They typically have thermal energy storage (TES) capability, which allows them to balance heat supply and production and to optimise income for electricity sales. This combination of DH, CHP and TES has proven to be very effective for integrating wind power due to its flexibility in regulating the fluctuations of wind power production [27], even though the system was introduced for different purposes.

The integration of RE in Denmark has been increasing over the last decades, mainly in the electricity supply, where wind power now contributes 39% of the total electricity supply and the share of RE overall is 53% [26]. The share of RE has also been increasing in terms of energy supplied to DH, where biomass currently contributes 46% to the total DH supply, and other sources such as solar thermal, geothermal and HPs also contribute, though so far with only a minor share [26].

The Danish Government has an ambition to transition the energy supply to being based on 50% RE in 2030 and 100% RE energy in 2050 [28]. A number of comprehensive studies of the Danish energy system and how this conversion could take place have been performed [29–35]. These studies use different assumptions, perspectives and methods, and show that it is possible to reach a 100% RE supply while maintaining a similar energy service level. Furthermore, these studies all include DH as a central part of the future energy system as a means of maintaining a cost and resource efficient energy supply.

1.2. SCOPE AND RESEARCH QUESTION

In the above sections, the background of today’s situation and challenges for the energy sector, and the role of DH in this, was introduced. Here, the scope and research question for this thesis is presented and, finally, the structure of the thesis described.

1.2.1. RESEARCH QUESTION

The aim of this thesis is to provide a coherent explanation of potential solutions to these challenges, which are based on a combination of the existing literature and the papers upon which the thesis is built. The following research question is thus formulated:

How should district heating systems and technology be developed in the transition towards a 100% renewable energy supply to meet societal goals of low socioeconomic costs and a sustainable use of energy sources?

To concretise the research question, three sub-questions have been formulated:

- *Which heat sources for DH should be considered in a RE system?*
- *How much will and should the heat demands be reduced in the future?*
- *How should DH supply and technology change to fit the new conditions?*

These questions are answered through a combination of literature review and own research. Each sub-question is addressed within a dedicated chapter (Chapter 3, Chapter 4 and Chapter 5). Each of these chapters begins by presenting aspects of answers that are available in the existing literature, followed by a presentation of the critical new pieces of information that are provided through the research and analytical work of this thesis.

Because of the large amount of research regarding 100% RE integration in Denmark and the large amount of experience and data on the actual operation of DH systems, Denmark is considered an interesting case for the analysis of future strategies for the development of DH.

Generally, a Danish national perspective is applied, considering socioeconomy rather than business or consumer economy; this allows for the drawing of conclusions on an overall level and enables the provision of recommendations for national planning, regulation and strategies. The case of study in this thesis is Denmark, but the conclusions may also be applied in other countries with similar conditions.

1.2.2. STRUCTURE OF THE THESIS

The thesis is structured into five main chapters, where the first two are *Introduction* and *Theory and Methods*. The following three chapters, containing the results and discussion, describe the transition of energy systems towards 100% RE and the role of DH in this transition. Chapter 3 presents the *Changing mix of heat sources*, Chapter 4 the *Reducing heat demands* and Chapter 5 *The need for changes in the district heating supply system.*

The six accompanying papers each contribute to one of these three areas, and the findings and contributions of the papers are presented in the corresponding chapters. Paper 1 compares and discusses two methods for energy system analysis and is mainly discussed in Chapter 2, but is also included in Chapter 5. Papers 2 and 3 consider two heat sources and their future potential; they are discussed in Chapter 3. Paper 4 assesses pipe heat loss in a system perspective and is presented in Chapter 4. Papers 5 and Paper 6 are included in Chapter 5 and discuss the future design of DH systems.

CHAPTER 2. THEORY AND METHODS

This chapter presents the theoretical understanding of the scientific area of the thesis. This includes the Choice Awareness theory and the Smart Energy System concept. In line with this, the choice of main methods used in the analytical work is presented and discussed. Finally, the energy systems analysis tool EnergyPLAN is presented and its application is described.

2.1. CHOICE AWARENESS THEORY

The theory of Choice Awareness is presented in [36] by Henrik Lund, and describes the public decision making process, with a focus on energy system infrastructure. The theory states that existing organizations and institutions, according to their own perceptions of the world and to maintain their existing positions, will influence public opinion and the solution choices available for achieving society's goals. Further, the theory states that society as a whole can benefit from promoting public awareness of technical, and potentially more feasible, alternatives to those suggested by existing organisations.

An organisation cannot be expected to produce or suggest a solution that removes the need for the organisation itself; therefore, significant changes in technical infrastructure are likely to meet opposition from the existing organisations and institutions. Frede Hvelplund defines a *Radical Technological Change* as a change that affects more than one of the following dimensions of technology [37]:

- Technique
- Knowledge
- Organisation
- Product
- Profit

In a situation where a solution constituting a radical technological change is suggested, existing organisations can be expected to try to eliminate that solution option, leaving only one or few solutions that comply with their perception of the world [36].

2.1.1. FOURTH GENERATION DISTRICT HEATING: A RADICAL TECHNOLOGICAL CHANGE

The fourth generation of DH, as presented in Section 1.1.3, is seen as a radical technological change for the purposes of this thesis. This perspective is used in the discussion of results and possible implementation.

The 4DH includes a number of changes to the existing way of supplying DH. It will require many more heat sources, which are smaller in capacity than the existing large central CHP plants. At the same time, these CHP plants will be required to produce much less electricity due to the increasing fluctuating electricity supply. This can create a dilemma, since the owners of large CHP plants are, in some cases, the DH companies themselves [38,39]. These DH companies may try to maintain a centralised production system, even though more distributed heat sources might be more feasible from a societal perspective.

In this way, the Technique, i.e. the mix of production units and their operation, will change. The Knowledge will also change with respect to the use and integration of new production units in the supply system. The Organisation should be revised to make sure that it fits a system with many smaller producers and an improved integration with the electricity and industry sectors. The Product can be seen as the total energy service of the energy system: supply of electricity for appliances, HPs, electric vehicles and heat supply from DH. Consumers may not notice large differences in the energy products they receive, but buildings will be more efficient, cars will be electric and the DH supply will be at a lower temperature.

Based on the above, it is clear that the implementation of 4DH will influence more than one of the five dimensions of technology, thereby qualifying as a radical technological change.

2.1.2. CHOICE AWARENESS STRATEGIES

Following the theory of radical technological change, the methodological framework called *Choice Awareness Strategies* is designed to promote and raise public awareness of technical alternatives to those presented by existing organisations and institutions [36]. There are four strategies described within the framework, which are listed here and further elaborated below:

1) Design of Concrete Technical Alternatives
2) Feasibility Studies Based on Institutional Economics
3) Public Regulation Measures Proposals
4) Promotion of New-Corporate Democratic Infrastructure

The design of concrete technical alternatives is a necessity for the above strategies. This includes a concrete technical modelling and assurance that the proposed alternative is a real alternative, in the sense that it should be able to cover the same demands, solve the same problems etc., as the reference solution. The first strategy of proving that technical alternatives exist does not always suffice to convince the public that the alternative is worth considering. Therefore, feasibility studies may be necessary to provide concrete parameters for comparison of different alternatives. Some important parameters that are of societal interest are socioeconomic costs, emissions from combustion of fuels and consumption of natural resources, which feasibility studies can provide [36].

In the alternatives assessment and feasibility study, it might become evident that current legislation or the existing regulatory framework does not support the most feasible technical solution, from a societal point of view. This would indicate that a revision of the current legislation or regulatory framework is necessary to enable the more feasible solutions. For example, if a feasibility study shows that heat savings are feasible from a societal perspective, but no business or private incentives are in place to promote this course of action, then the strategy is unlikely to be implemented, even though society overall would stand to benefit. In this case, an increased fuel tax, investment subsidy for energy refurbishments or similar changes in the relevant regulation would support the societal goals by creating an incentive structure that aligns private incentives with the interests of the society. The last Choice Awareness strategy of promoting democratic infrastructure deals with the question of *Who* should take up the tasks in pushing for feasible radical technological changes. As mentioned, it cannot be expected that existing organisations and institutions will act in favour of radical technological change because such change is likely to conflict with or devalue their inherent functions and interests. Therefore, it is argued that, in principle, representatives from emerging technologies found among citizens, non-governmental organisations, new small companies and policy makers should be the ones to promote the change. However, this is a complicated process, influenced by many interests; but, if successfully done, this can improve the implementation of the first three strategies [36].

The analyses presented in this thesis primarily focus on the strategies of designing alternatives and feasibility studies. In some cases, the need for revised public regulation measures are discussed, but without going into details of how the public regulation measures should be designed.

2.2. SMART ENERGY SYSTEMS

Smart Energy Systems is a conceptual approach for energy system analysis and energy system design within the context of a development towards 100% RE.

2.2.1. INTEGRATION OF SECTORS

This concept emphasises the integration of the isolated energy sectors (electricity, heating, transport, industry, etc.) into one integrated smart energy system (see Figure 3). In [40], smart energy systems are described as the combination of:

- Smart electrical grids
- Smart thermal grids
- Smart gas grids

Intelligent – or *smart* - operation of these three grid types is also mentioned as an important aspect of smart energy systems, as it is due to the intelligent interaction between supply, demand and storage that the benefit is achieved. In [41], it is mentioned that especially fuel storages and thermal storage in DHC systems have large potential for cost-effectively improving system flexibility because of the low costs per storage capacity compared to electrical storages.

To be able to intelligently manage the operation of the smart energy system, flexible conversion units need to be installed in the energy system. This flexibility refers to these units' ability to regulate their production up or down or to change from one energy source to another. An example could be when wind power production increases, the output of a CHP plant could be reduced and the subsequent reduced heat production could be replaced by production from HPs.

An important part of sector integration in 100% RE systems is related to the fuel and transport sectors. The key idea is the flexible utilisation of electricity for gas and liquid fuel production. This can be achieved through large scale electrolysers, combined with biomass gasification and chemical fuel synthesis. In this way, fuel an transport demands can be covered using RE sources, limiting the quantity of biomass needed [42,43].

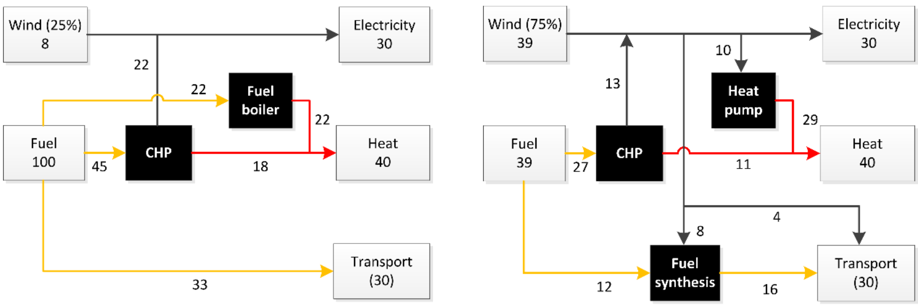

Figure 3: Illustration of the change from a conventional CHP system (left) to a "Smart Energy System" (right). White boxes indicate supply and demand and black boxes represent conversion units. Black arrows indicate electricity, red represent heating and orange show fuel flows.

2.2.2. BIOMASS CONSUMPTION

In a 100% RE system, biomass is a critical resource, as this will be the only natural fuel left when fossil fuels have been phased out. Biomass can be used for essentially all the same purposes as fossil fuels, but a direct replacement of fossil fuel with biomass on a global scale is not viable because that would create an over exploitation. In 2015, global primary energy consumption was 550 EJ, where less than 3% was provided by RE [44]. In the study Coherent Energy and Environmental System Analysis (CEESA), which is summarised in [45], the global biomass potential is reviewed. The World Economic Council (WEC) [46] and The International Energy Agency (IEA) [47] both makes assessments ranging between 50 and 500 EJ, depending on the intensity of energy crop farming and the emergence of new alternatives such as algae farming. The Danish think tank Concito’s assessment [48] of the global biomass potential is much lower, ranging from 15 to 100 EJ, due to strict sustainability requirements for the biomass. In [49], an assessment of European conditions finds that the biomass potential is much lower than current demand - about one fourth. In CEESA, the Danish biomass potential is assessed at 240 PJ, which is at the high end of the IEA and WEC assessments on a per capita basis, so most other countries have a lower per capita potential than Denmark.

This means that substantial amounts of energy will have to be provided from sources other than biomass, especially if an increase in future energy demand is assumed. The WEC estimates that a maximum of between one fourth and one third of the global energy supply can be covered by biomass [46]. One of the key aspects of smart energy systems is that energy systems should be designed to not consume more biomass than is necessary or sustainable. In the study presented in [22], the use of biomass for heating is discussed in the context of a smart energy system; specific solutions are suggested to limit the consumption of biomass to a sustainable level. Similarly, it is shown in [50] that it is more feasible to reduce biomass consumption for heating compared to the electricity sector.

2.2.3. SCENARIOS FOR DENMARK

The CEESA study from 2011 provides an example of an analysis applying a smart energy systems approach. This study seeks to design a cost and resource efficient energy system for Denmark based on 100% RE, which, on average, does not consume more biomass than the available marginal biomass resources in Denmark. Special focus is placed on the transportation sector, where different pathways for meeting 100% RE, using domestic resources, was assessed [40] [45]. Another study that applies a smart energy system approach is the IDA Energy Vision from 2015. This study also analyses options for 100% RE energy supply in Denmark in 2050, with an interim step in 2035. In this study, additional attention is put on the Danish energy system in the context of the European energy markets, considering the sensitivity of the uncertainties that these markets imply [35].

The smart energy system is well in line with the 4DH systems presented in this thesis because of the shared focus on sector integration, fuel efficiency and cost-effectiveness. The smart energy systems concept is therefore used as the guiding energy system approach for the transition towards 100% RE system, using the CEESA and IDA Energy Vision models as starting points for the specific analyses presented herein.

2.3. ENERGYPLAN

EnergyPLAN is the main analysis tool applied in the analyses presented in this thesis and has also been used in the accompanying papers [1,2,4–6]. EnergyPLAN is therefore of critical importance for the results of the thesis. The general purpose and application of using the tool is presented here; in Section 2.4 some weaknesses of EnergyPLAN will be discussed with other approaches for energy systems analysis and modelling.

EnergyPLAN has been developed at Aalborg University by the Sustainable Energy Planning research group in the Department of Development and Planning. The tool has been developed gradually, since its first version in 1999, to enable it to handle increasingly complex energy systems and to model particular issues of relevance for scientific and societal development in energy systems [51].

The fundamental idea of EnergyPLAN is highly connected to the Choice Awareness Theory. It is designed to promote the Choice Awareness strategies presented in Subsection 2.1.2, particularly the development of concrete technical alternatives, but also to support the design of feasibility studies and public regulation measures. EnergyPLAN enables the user to calculate how an energy system operates over one full year, on an hourly time resolution. It is structured around a number of inputs that define a model of a system of interest for the specific study. It provides output indicators on an annual basis, such as total fuel consumptions, system costs and CO_2-emissions, but also allows for the review of detailed hourly parameters.

Figure 4 shows a flow diagram that contains the core resources, conversion technologies and demands that are incorporated into EnergyPLAN. The tool basically simulates one year of operation, in hourly time resolution, of the exact system defined by the inputs. Demand, conversion and storage capacities, efficiencies, fuel mix of different units and costs are all considered as inputs. The model does not alter or optimise any input parameters, but the simulation can be adjusted for different purposes and to prioritise different methods of meeting the demands. For example, EnergyPLAN can run simulations to operate the system in the most fuel-efficient way or to reduce the marginal operation costs for heat and electricity producers.

Taking the above mentioned characteristics into account, EnergyPLAN is a very well suited tool for modelling and analysing 100% RE integration and smart energy systems, which has been central in the research for this thesis. The tool has also been used for analyses of 100% RE and smart energy systems scenarios in [12,21,25,40,41,52,53]. The scenarios CEESA and IDA Energy Vision have both been developed for analysis in EnergyPLAN. These models have been made available for use in this thesis and form the starting points for implementation of the different scenarios developed herein.

For the analysis presented in [6], which compares low-temperature DH scenarios, the EnergyPLAN model was customised to be able to model time dependent coefficients of performance (COPs) for HPs in DH. This was done for that particular study because the COP of HPs is very sensitive to the temperature level in DH systems in low temperature DH regimes, but is less sensitive at higher temperatures. Therefore, to compare these scenarios properly, including seasonal variations and for systems where HPs play a significant role, this issue was seen as an important aspect to include.

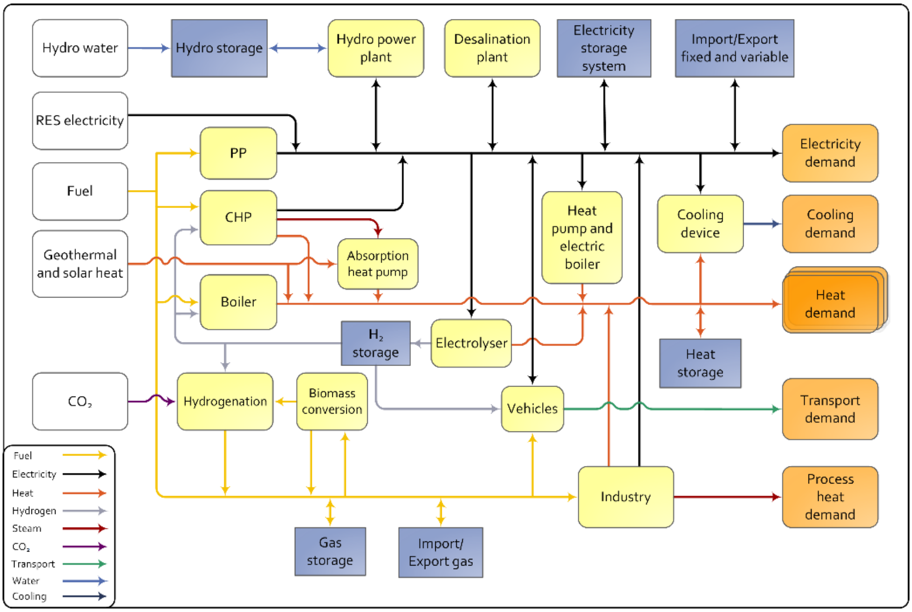

Figure 4: Flow diagram representing the core resources, conversion technologies and demands in EnergyPLAN. (Figure colors: White - Resource, Yellow - Conversion unit, Blue - Storage and exchange, Orange - Demand)

2.4. APPROACHES FOR ENERGY SYSTEM ANALYSIS (PAPER 1)

In this section, the choice of energy system analysis method is discussed, based on the findings in [1]. In [1], two different analysis methods encompassed in two tools (MODEST and EnergyPLAN) are applied to conduct the same analysis. The results are compared and discussed with respect to the differences between the two tools, reflecting the two inherent modelling approaches.

2.4.1. ENERGY SYSTEM ANALYSIS TOOLS

Figure 5 shows a conceptual diagram of an energy system analysis tool. The energy system analysis tool shown here is considered to represent the framework in which a concrete energy model is defined based on a number of model assumptions. The concrete model is then applied and the analysis is performed using the tool. Additionally, some analysis parameters concerning the operation of the tool are chosen for the generation of a number of outputs. For the analysis presented in [1], the two tools are compared based on the same model assumptions and analysis parameters and the output parameters drawn from the analyses are the same. This is done to isolate the difference in results caused exclusively by the computational analysis procedure.

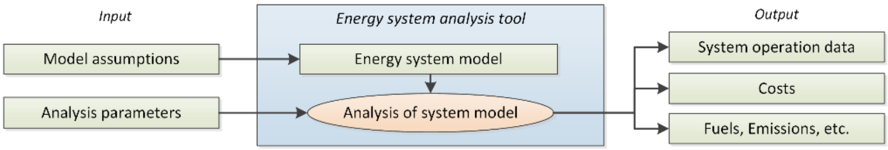

Figure 5: Conceptual diagram of an energy system analysis tool with inputs and possible outputs [1].

The use of modelling and calculation tools for energy systems analysis is very common and helpful in organising and structuring, in a systematic way, the large amounts of information on the components and relations within an energy system. This moves some tasks from the researcher to the tool, which is convenient, but also introduces a risk. The risk is that the tool does not calculate as the researcher expects it to. Therefore, a new and critically important task arises when using a tool: the researcher must check that what the model actually does is in accordance with what the researcher wants to analyse, otherwise the outputs can be misinterpreted. Analysis using a tool will therefore often be a circular process, where the output leads to a new realisation that subsequently feeds into the definition of the model inputs, thus altering the way in which the outputs are interpreted by the researcher.

2.4.2. DIFFERENCES BETWEEN MODEST AND ENERGYPLAN

The main differences between the two tools, MODEST and EnergyPLAN, are presented in Table 1, based on [51,54]. The first parameter, the modelling approach, is a determinant for many of the other parameters. The cost optimization function in MODEST allows for the determination of the optimal value of selected parameters, within a certain setting. This is not possible in EnergyPLAN, where an optimization must be done manually by trial and error, and optimising more than one parameter at a time can be very time consuming, if not impossible. On the other hand, the optimisation algorithm is more computationally demanding in MODEST than is EnergyPLAN's simulation method. EnergyPLAN can therefore perform calculations on an hourly resolution over a full year faster than would be possible with an optimisation tool, especially for complicated models with many variables. This is also a reason for the limit in temporal resolution and model complexity (Aggregation level) in MODEST.

The temporal resolution of the model analysis is a central difference between the models. This has a particular influence on modelling the storage function. In EnergyPLAN, it is modelled on an hour to hour basis, with charge and discharge dependent on the balance in the system. In MODEST, on the other hand, storage is modelled between similar groups of hours through each month. This makes the operation of storage in MODEST more hypothetical in nature, and the influence of short term fluctuations in energy supply and demand will not be captured. Though whether this presents a problem for the reliability of results is another question.

Table 1: Comparison of MODEST and EnergyPLAN on computational analysis procedures and functions.

	MODEST	**EnergyPLAN**
Modelling approach	Cost minimization	Simulation
Result	Operation of optimised system	Operation of user defined system
Time divisions	Up to 99	8784
Years of operation	Up to 99	1
Model design	User defined	Predefined options
Temporal operation	Depending on time divisions	Continuously from hour to hour
Aggregation level	User defined - Max 400 nodes	Aggregated on plant types
Calculation horizon	Full knowledge	Hourly (except storage)

2.4.3. COMPARISON OF MODEL RESULTS

The analysis is performed for the case of Denmark for a 2025 scenario with large-scale integration of fluctuating RE. The DH HP capacities are the only variables defined for optimisation in MODEST. In EnergyPLAN, the HP capacities resulting in the lowest total costs are found by trial and error. The full analysis can be found in Paper 1. Figure 6 shows the results of the main scenario (Base line) and some sensitivity analyses for different parameters. The models provide generally the same result trends, though two differences can be seen in the figure: MODEST typically calculates higher total system costs and higher optimal HP capacities. The reason for this is that the thermal storages are not used as efficiently in MODEST as in EnergyPLAN. In MODEST, the amount of traded electricity is generally higher than in EnerygPLAN, and the total fuel and electricity trade cost is higher in MODEST in every calculated case for the 2025 scenario.

This indicates that the modelling method for storage in MODEST is not as good for this analysis, which considers large-scale integration of fluctuating RE, mainly wind power, because the fluctuations only to a very small extent correspond to the time of day and year. In such cases, it can be concluded that using an optimisation model does not ensure that produced “optimal” solution is actually an optimal solution, since the solutions found in EnergyPLAN identify lower optimal HP capacities and have lower total costs.

The MODEST tool allows for modelling a concrete DH system in much more detail than what is possible in EnergyPLAN, which could have been utilised in this analysis and potentially could have provided a more accurate result. For example, it was not possible to model each single CHP and power plant in EnergyPLAN. As the purpose of the study was to compare results using the exact same data input in the two models, this option was also not used in MODEST. This process could be seen as limiting the potential of MODEST, and therefore may not represent the best way of using the tool.

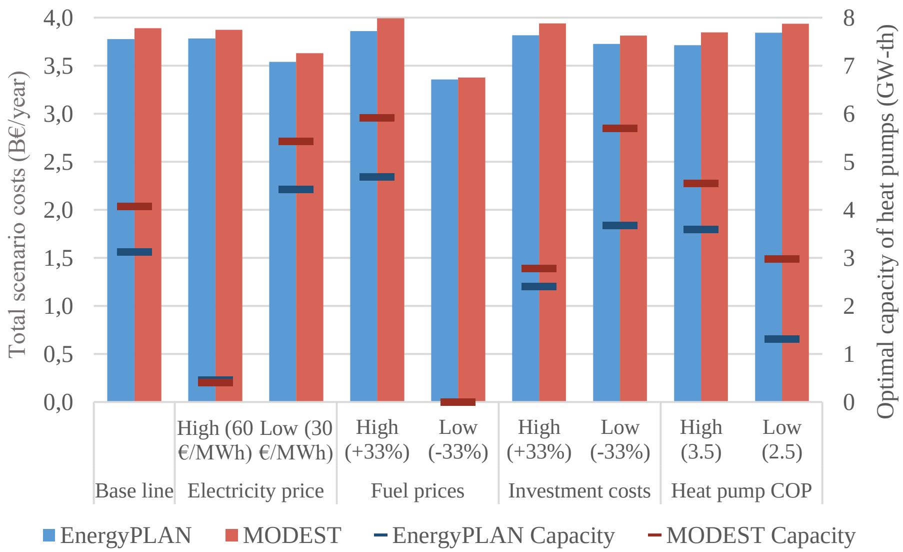

Figure 6: Diagram showing results of the sensitivity analysis of external electricity price level, general fuel price level, investment costs for heat pumps and average COP of heat pumps for district heating, in a 2025 scenario for Denmark. Line markers indicate optimal capacity of heat pumps. The full analysis is presented in [1].

In an analysis of a more traditional energy system, the MODEST tool will likely identify better solutions than EnergyPLAN because of its optimisation procedure. In systems without parameters with large fluctuations that are independent of the time of day and year, like wind power, the degree of detail in time resolution and storage modelling becomes less important, because the average daily patterns will be accurate much more often.

As a conclusion to this discussion, it can be said that the choice of energy system analysis tool should be carefully made according to the specific analysis' purpose, considering the central aspects of the analysis and the characteristics of the possible alternative tools.

CHAPTER 3. CHANGING MIX OF HEAT SOURCES

This chapter first presents current tendencies and challenges in the mix of heat sources for DH production. Thereafter, some considerations regarding sustainability of heat sources in a smart energy system are presented. Finally, the contributions from Papers 2 and 3 are presented.

3.1. CURRENT TENDENCIES AND CHALLENGES

The mix of heat sources in an energy system changes gradually as the focus on environmental issues and climate change increases and the costs for new technology decreases. The integration of large shares of wind power in has had significant impacts on the Danish energy system. At the same time, coal is being phased out of the DH supply, leaving a large gap that needs to be replaced by new heat sources.

3.1.1. DECREASING CHP PRODUCTION AND CAPACITY

In Denmark during the last decade or so, the operation of CHP plants has become less feasible, which has resulted in less production of heat in combination with electricity. In Figure 7, it can be seen that the heat production share from central and decentral CHP plants has been decreasing for the last 15 years and, at the same time, the share of DH has been increasing, to about 52% today. The heat replacement has mainly come from heat-only plants, which is a diverse group of plants. The current majority, by far, are fuel boilers, but also solar thermal, geothermal, electric boilers and HPs are included in this group [26].

There are a number of reasons for the decreasing DH production from CHP plants. The main reason is that the average electricity prices in the Nordic electricity market, Nordpool, has been decreasing, particularly over the last five years, which has made it less feasible to produce electricity, thereby reducing the competitiveness of CHP units [55]. Another reason is that several of the existing central CHP plants have been decommissioned over the last decade [56]. Decentral CHP capacity has also decreased, partially due to the fact that the basic payment[1] ends in 2018. According to the Danish TSO, Energinet.dk, the capacity of central and decentral CHP plants will continue to decrease in the coming years [57]. A survey of most decentral plant

[1] The capacity payment is a public subsidy scheme for decentral electricity producers who participate in the electricity market, and it inversely corresponds to the income from electricity sales.

owners reveals that many will not prolong the lifetime of their CHP units, and very few will reinvest in new units after 2018 [58].

3.1.2. INCREASING BIOMASS CONSUMPTION FOR HEATING

Another significant tendency in the current development of the DH sector is the replacement of fossil fuels with biomass. In Figure 8, the total DH production in Denmark is presented with the trend of the fuel mix. It can be seen that Renewable Energy is increasing as coal consumption decreases. In 2014, the Renewable energy category included: 96% biomass, 3% biogas, 1% solar thermal and less than 1% geothermal and HPs. Biomass consumption includes both boilers and CHP plants in central and decentral DH areas [59]. Electricity consumption for electric boilers is also negligible in the big picture, with less than 0.5%.

The increasing tendency of biomass consumption is expected to continue, especially for large CHP plants. This is due to a change in the levy structure for biomass consumption for large CHP plants, which increases the incentive to convert coal-fired CHP plants to biomass-fired CHP [60]. This has induced several plans for conversion of old CHP plants from coal to biomass [59,61–64]. These plants are designed using similar concepts as the existing coal-based CHP plants, but with a greater focus on high heat output. The discourse around these conversions and new plants primarily focuses on low CO_2-emmissions and “green energy,” but whether these types of plants fit into long-term RE scenarios is not considered – or at least not mentioned.

3.1.3. SUMMARY OF CHALLENGES

Based on the above presentation of the current development in heat sources for DH, and considering the smart energy system concept presented in Section 2.2, some challenges can be identified.

The smart energy system concept suggests the integration of energy sectors to utilise synergies between sectors to accommodate for increasing fluctuations from RE generation. But, currently, CHP production and capacity is decreasing, and is not being replaced with smart solutions, such as HPs. It is mostly being replaced with fuel boilers, which represent more of a disintegration of electricity and heat. Secondly, biomass consumption should be allocated to processes that cannot easily be covered by electricity or other sources of energy. However, biomass is increasingly being used for heat production in the current DH system, driven by a public incentive to do so. The current development is therefore, with respect to these two central questions, moving towards a less “smart” system.

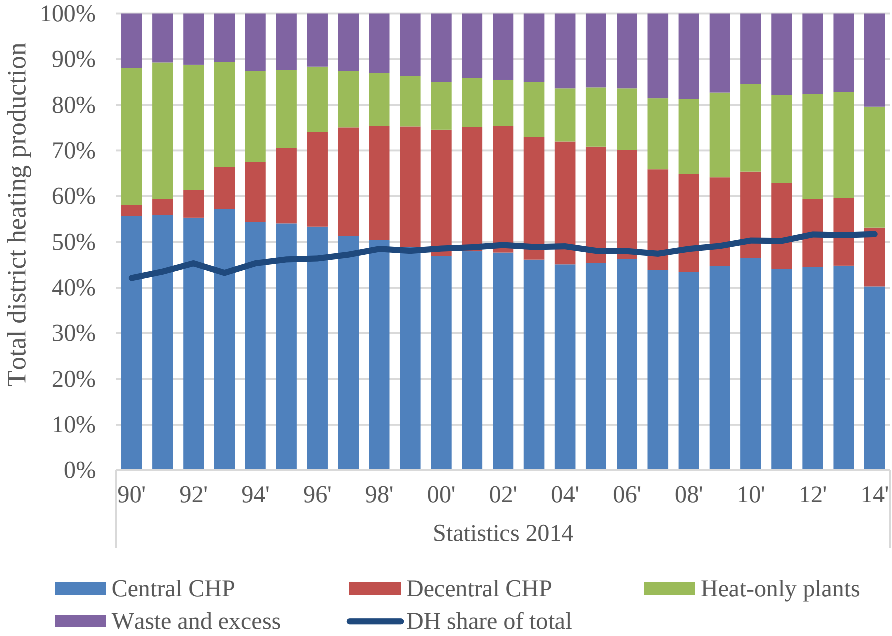

Figure 7: Historical development in the mix of production units for district heating production and the share of the total heating demand which is covered by district heating in Denmark [26].

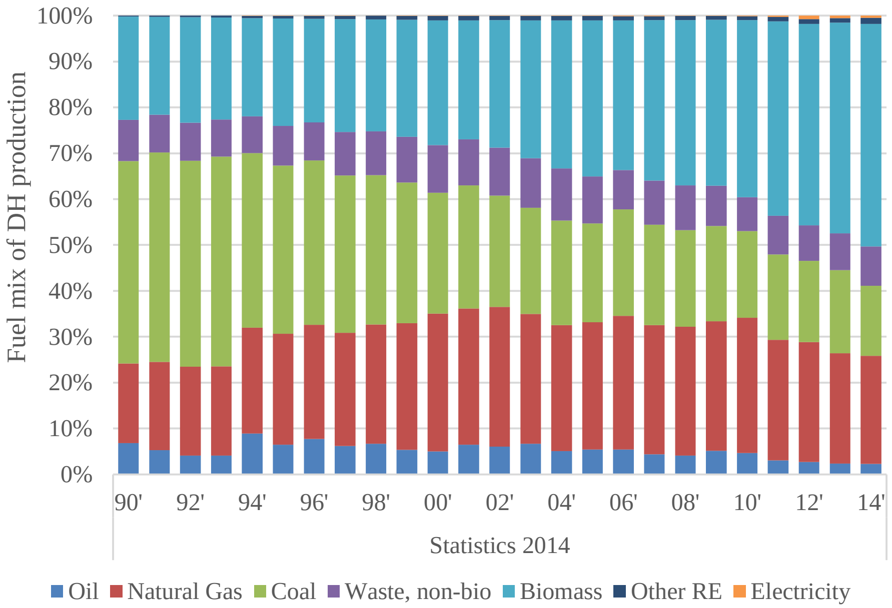

Figure 8: Historical development in the fuel mix for district heating production in Denmark [26]. Biomass accounts for 95% of the category "Biomass and other RE".

3.2. HEAT SOURCES FOR SUSTAINABLE HEATING SUPPLY

In the project IDA Energy Vision 2050 a 100% renewable energy scenario is designed and presented, where a combination of different system components and heat sources are assumed [35]. In comparison to today's system, a large share of new heat sources is expected to be a part of the heat source mix. Figure 9 shows the combination of heat sources for the 2015 system compared to the 2035 and 2050 scenarios in the IDA project. The 2015 column can be seen as a continuation of the one for 2014 in Figure 7, where the historical development can be seen. The orange parts indicate the new heat sources that will replace production from the existing system components.

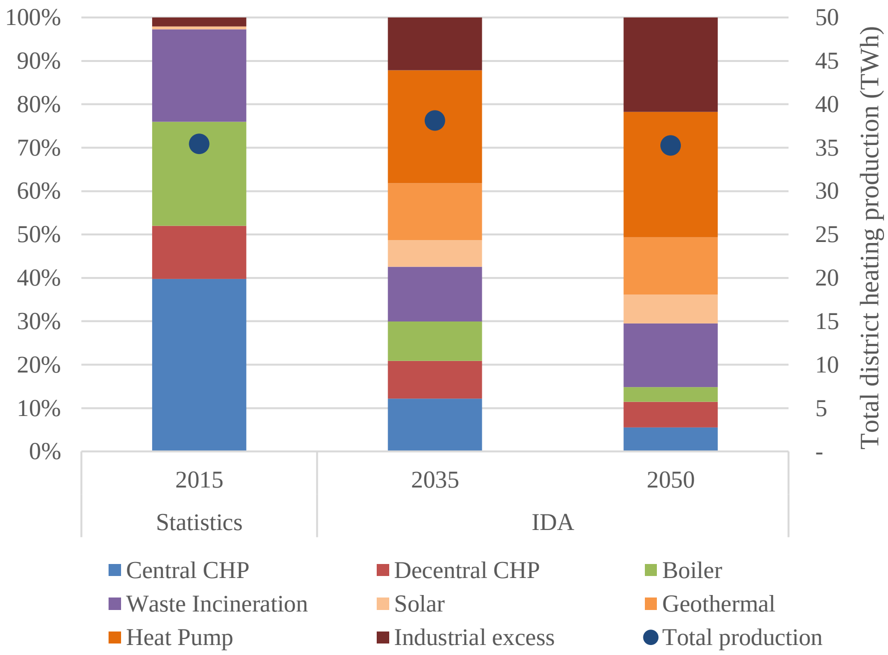

Figure 9: Existing district heating production mix compared with the potential future development described in the IDA 2035 and 2050 scenarios.

As seen in Figure 9, the new heat sources, solar thermal, geothermal and HPs, will contribute 50% of the DH production in the IDA 2050 scenario. The contribution from Industrial excess heat is also increasing because it is assumed that more of the potential will be utilised and, at the same time, more efficient supply systems will enable a larger output from the existing suppliers.

Two central points of this development are further investigated and discussed in the following sections. The first is the role and the need for large CHP plants as a heat source for DH in future energy systems, considering the changing needs on the electricity side. The second issue is the potential supply of heat from HPs, and whether there are heat sources for them that should be considered for large scale integration, as different studies suggest.

3.2.1. THE ROLE OF LARGE SCALE CHP IN THE FUTURE (PAPER 2)

In Paper 2, four different large-scale CHP plant (extraction plant) types are compared in the context of a 100% RE system. In this paper, the CEESA 2050 Recommendable scenario is applied [45]. The idea is to compare biomass fired CHP plants, which are commonly suggested and planned for, as presented in 3.1, with gas-fired CHP plants, which are suggested in both the CEESA and the IDA studies on smart energy systems.

In the analysis, combined cycle gas turbine (CCGT) CHP plants are compared with advanced pulverised fuel (APF) plants and two different installed capacities of circulating fluidised bed (CFB) plants (CFB Low and CFB High). Table 2 lists the assumed installed capacities considered in the scenarios. The thermal and electric efficiencies are some of the main characteristic differences between the plant types, which makes it necessary to have different capacities for electric and/or thermal output; this is a sensitive parameter, which is also why there are two capacity sets for the CFB plant type.

Table 2: Definition of capacities of thermal and electric production of the CHP plants in the four scenarios. The CCGT scenario capacities are defined in the CEESA scenario [2].

	CCGT	CFB Low	CFB High	APF
CHP electric capacity (MW-e)	2,500	850	2,000	2,500
CHP thermal capacity (MW-th)	1,290	1,290	3,050	2,690

The main results of the study are presented in Figure 10. The figure shows that the CCGT scenario has the lowest costs and biomass consumption. The CFB Low scenario is very similar, but the 850 MW-e is a very low total CHP capacity compared to the capacities today, and if the capacity is increased towards the CFB High scenario, then both costs, but particularly biomass consumption, increase significantly.

This indicates that CHP plants consuming wood chips (CFB) or wood pellets (APF) are not feasible in a long-term 100% RE system in Denmark. The main reason is that the larger electric efficiency and operational flexibility of the CCGT plant makes it more suitable in a smart energy system, even though the total efficiency of the plant is lower than the CFB plant. The flexibility aspect is central because of the need to integrate large amounts of fluctuating RE.

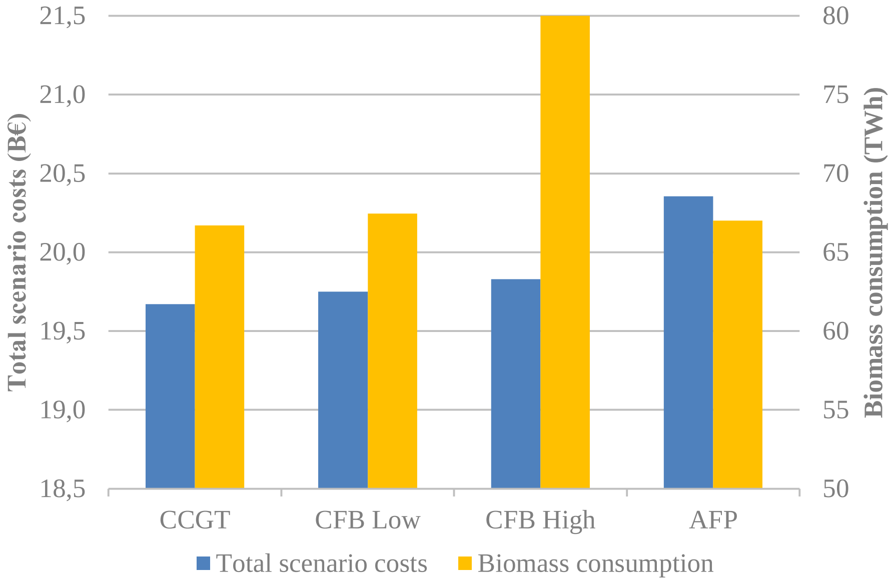

Figure 10: Main results for the scenarios of the technical energy systems analysis showing values for the whole energy system [2].

A market economic analysis of the scenarios indicates that it might be feasible to introduce some public regulation to limit the use of biomass for heat-only production – here analysed as a simple tax on biomass - since the biomass consumption for heat-only production would otherwise be higher. At the same time, this regulation would reduce the total socioeconomic costs.

3.2.2. HEAT SOURCES FOR HEAT PUMPS (PAPER 3)

In Paper 3, an analysis of the potential heat sources for HPs in Denmark is presented. A number of potential heat sources are mapped using a geographical information system (GIS) and considering the location of district heating networks. The included heat sources all have low temperature ranges that require HPs for boosting the temperature for DH supply. The included heat sources and their determined availability to DH networks as well as the potential heat volumes are presented in Table 3.

The results should be seen as a technical potential of heat sources and not a feasible potential. Large portions of the listed heat sources will not be feasible given the concrete conditions in the DH system due to, for example, large shares of industrial waste heat. The annual temperature levels of the heat source and DH network are also important parameters in their feasibility, as a low temperature DH system improves the sources’ COPs and thereby their feasibility [6].

The results for availability show that 99% of DH areas have access to heat sources for HPs. The sum of the potential heat volumes is approximately 18 TWh (excl. sea water), and represents the heat source input for the HPs. This means that if this entire heat volume were utilised by HPs, assuming a COP of 3, the total heat output would be 27 TWh. Comparing this to the assumed amount of heat output from HPs in the IDA scenario of approximately 10 TWh, it is apparent that the potential heat sources in Denmark can easily provide that.

*Table 3: Summary of analysis results for availability and potential heat volumes of the different heat sources. *This indicates a value calculated in [65] for large-scale industry.*

Heat source	Geographical availability of heat source (%)		Potential heat volumes (TWh)
	To no. of DH networks	To heat demand	
Low-temperature industrial excess heat	17.1	64.6	3.4*
Supermarkets	61.5	95.8	0.4
Waste water treatment	34.5	68.0	2.9
Drinking water	31.0	78.8	0.8
Ground water	98.8	99.8	6.9
River	8.4	30.7	3.2
Lake	7.7	21.9	0.7
Sea water	28.8	65.3	-

A challenge found in the study is the geographical distribution of heat sources, which is not proportional to the heat demand in DH systems. There is generally a lower ratio of heat sources per heat demand in the larger cities. This means that heat sources with lower potential COPs, mainly sea water, must be considered to a larger extent for use in big cities compared to small ones, to meet the capacities assumed in e.g. IDA Energy Vision.

The various heat sources require different technical solutions related to the heat source intake and the temperature range of operation. Ground water will have a constant temperature during the year, whereas sea water will have large changes during the year, being especially low during winter when heat demand is highest. Waste water, lakes, rivers and sea water may involve challenges when it comes to avoiding clogging of filters or heat exchangers, which requires technical solutions. In general, there is a need for many different technical solutions to fit each set of conditions. Many components for the solutions already exist, but the demand for HP solutions for DH production is not yet large. Additionally, it is important to further improve the ability of HPs to operate within the different temperature conditions to be able to use as many different heat sources as possible.

3.3. SUMMARY

In the transition towards a RE system, heat sources will need to change to cover the heat demands while keeping the consumption of biomass to a sustainable level. CHP plants will produce significantly less heat than today, and, in a future smart energy system, will play a larger role in balancing electricity supply and utilising their excess heat only when needed. A number of new heat sources will play an important role in the phase out of CHP and heat only boiler production. These sources will mainly be comprised of HPs, solar thermal, geothermal and industrial excess heat. HPs will be especially important because of their ability to use low-temperature heat sources for the supply of DH at a high efficiency. It has been shown that there are potential heat sources for HPs near all DH systems in Denmark, but that the geographical distribution of the heat source volumes is not proportional to the demands.

Table 4 presents an overview of the main differences between heat sources and production units within the contexts of the current DH system and a future smart energy system. Fuel boilers are included in the future system, even though their production is small, because they can have an important function in the heat supply for peak load production.

Table 4: Overview of main differences between heat sources today and in 2050.

Parameter	**Today (2015)**	**Future (2050)**
Generation of DH	2nd / 3rd	4th
Distribution of production	Partially decentralised	Highly decentralised
Number of producers	Few	Many
Fuel cost sensitivity	Medium	Low
Flexibility based on	Fuel consumption	Sector integration
Main heat sources:		
- CHP	X	
- Fuel boiler	X	X
- Waste incineration	X	X
- Heat pumps		X
- Solar thermal		X
- Geothermal		X
- Industrial excess		X

CHAPTER 4. REDUCING HEAT DEMANDS

Heat demand refers to the need for heating in a building. This depends on the outdoor temperature, thermal comfort level, insulation level of the building, number of inhabitants, behavioural parameters, etc. Some of these parameters vary between different countries and climatic regions, which generates different total demands. In the Ecoheatcool project the heat demands across Europe have been analysed. The results show that the variation in heat demand from Madrid to Stockholm is only within a range of ±20% of the defined index of 100 [66], where Denmark is at an index of about 110. This indicates that the variation in potential solutions across Europe is not that big.

4.1. FEASIBILITY OF HEAT SAVINGS IN A DISTRICT HEATING SYSTEM

When heat savings are implemented in an area with DH supply, the assessment of the feasibility of heat savings becomes significantly more complicated than when considering individually heated buildings. In Figure 11, the balance between reductions in heat demand and costs for heat production in DH systems is illustrated, based on [52]. The costs for reduction in demand are low in the beginning, when demand is high, but costs increase as demand falls because the interventions needed to further lower demand levels become increasingly costly. Production costs, on the other hand, are relatively stable with a slightly decreasing tendency because of a lower need for peak production capacity. This creates a point at which the costs for increasing supply become lower than the savings from further reducing demand.

Sperling and Möller conducted an assessment of the feasibility of heat savings in local DH system [67]. Their study shows that the marginal cost for heat savings is lower than the marginal cost for heat production, which means that, in this case, it is feasible to implement heat savings. The study also concludes that an expansion of the DH area is feasible. The same tendency is found for the case of Denmark in IDA Climate Plan 2050 [68] and Heat Plan Denmark 2010 [30]. In the latter, it is suggested to reduce the SH demand by 50% and expand DH to cover 63-70% of the total heating demand in Denmark (DH currently covers about 52%). These two developments would generate a synergy, reducing both fuel consumption and total socioeconomic costs.

Implementing heat savings has also been shown to be feasible in a broader European context – including where DH is present. The study by Hansen et al. [69] analyses the balance between heat savings and supplying heat for four European countries: Czech Republic, Croatia, Romania and Italy. The study finds that between 30 and 50% heat savings are feasible for the different countries, depending on the specific national conditions.

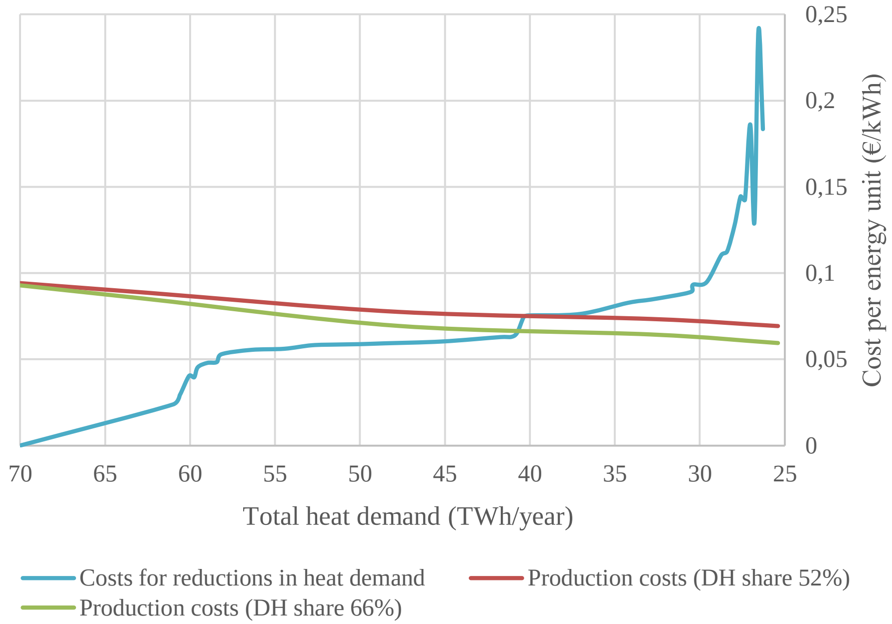

Figure 11: : Marginal cost of heat production in the overall Danish energy system in year 2050 compared to the marginal cost of improving energy efficiency in buildings [52].

In [70], Connolly et al. analyse the 27 member states of the European Union (EU27) as whole. This study finds that combining 50% DH coverage with substantial heat savings in the EU27 would reduce the costs for heating and cooling by 15%, equivalent to 100 B€. Similarly, it is found in [71] that heat savings and DH in a 100% RE scenario for Europe in 2050 is feasible without consuming an unsustainable amount of biomass.

The heat supply from DH plants depend on several factors, as illustrated in Figure 12. SH causes the main differences throughout the year; it is influenced by temperature changes over the year and is determined by the insulation of the buildings, which can be improved through technical means. The DHW varies on a daily basis, but is relatively constant throughout the year and is not easy to reduce using technical means; as such, it is usually not considered as a potential for heat savings.

The indicated potential savings in grid loss and SH in Figure 12 are the same as those applied in [6], where the potential savings in SH is 45% in existing buildings, and an increase in heated area is considered with new well insulated buildings. This leads to a total reduction of 34% of the total SH demand. As seen in the figure, because SH savings lead to large reductions in the SH peaks, the required production capacity for peak load can be significantly reduced. In this case, the peak load is reduced by 28%, which translates into direct savings in peak load unit capacity.

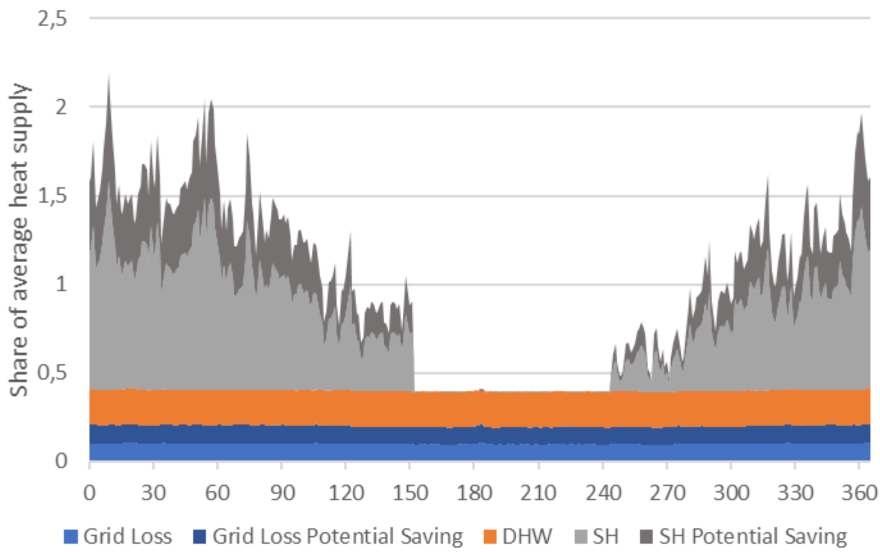

Figure 12: Annual DH supply profile in a system where grid losses account for 20% of the annual supply. Of the demand, which includes domestic hot water (DHW) and space heating (SH), DHW accounts for 25%. The potential saving in grid loss is 50% and for SH it is 34%.

Savings in pipe losses are similar to savings in SH, in the sense that both require large investment costs, but will save expenses elsewhere in the energy systems, e.g. fuel or production capacity. However, reductions in pipe losses also differ from SH savings, because grid loss has the characteristics of a base load in that it has no significant peaks, unlike SH. Therefore, grid loss savings have a different influence on the energy system, which should also be studied in the context of a 100% RE system.

4.2. REDUCTION OF LOSSES IN PIPE NETWORKS (PAPER 4)

Paper 4 focuses on the assessment of the potential in reducing heat losses from DH pipe networks. Four different scenarios are considered, defined by different pipe insulation series (Series 1-4), where S2 generates a reduction in heat loss of 14%, S3 - 29% and S4 - 44%. The scenarios are compared for 2013 and 2050 using the CEESA 2050 Recommendable scenario as a starting point, in which substantial SH savings have been implemented.

The analytical method used is a combination of a detailed thermodynamic model for DH pipe network analysis for the calculation of potential heat loss reductions and the EnergyPLAN tool for the calculation of the energy system implications. The scenarios are compared according to total system costs and fuel consumption. The main economic results of this study are presented in Figure 13.

The results show that the S3 scenario (series 3 pipes) incurs almost the same costs as both the reference scenario and the S2 scenario, and considering that S3 has greater fuel savings, this scenario is preferred from an economic perspective, compared to a reference scenario which is a combination of S1 and S2 pipes. The costs for the S4 scenario are significantly higher than the other three, but the fuel savings are also higher, so depending on the scarcity of biomass, S4 might be the preferable scenario.

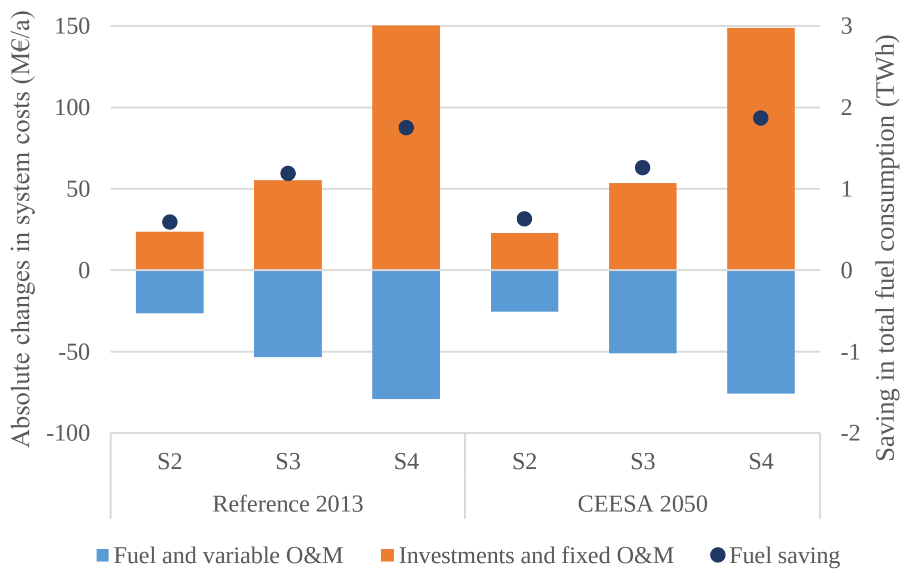

Figure 13: Changes in total annual costs in the alternative scenarios divided into variable and fixed costs. The scenarios are related to the Reference scenario on the secondary axis. S2-S4 refers to pipe insulation series 1-4.

4.3. SUMMARY

The current heating demand should be significantly reduced in the development towards a 100% RE system to maintain a cost-effective energy supply. Heating demand has an influence on the primary energy supply, but also on the needed production capacities in the energy system. If demand is reduced, savings can be obtained in both fuel consumption and capacity investment costs in boilers, CHP units, HPs, etc. Investment in the reduction of SH is generally a feasible strategy, but investments in better insulated DH pipes have also been shown to reduce fuel consumption of the energy system without increasing costs; moreover, if a socioeconomic increase in costs can be accepted, then fuel consumption can be further reduced. Table 5 presents the main differences between the current and future energy system in relation to heat demands.

The future feasibility of DH may depend on changes and improvements in the mix of heat sources, system design and sector integration, but its feasibility is robust to the level of implemented heat savings. This means that in a smart energy system, DH is feasible even if no further heat savings are implemented.

Table 5: Overview of main differences between heat demand today and in 2050.

Parameter	**Today (2015)**	**Future (2050)**
Generation of DH	2nd / 3rd	4th
Focus in building efficiency	Low heat demand of new buildings	Low heat demand of existing and new buildings
Heat losses from building stock	Medium	Low
Share of DH in EU (Denmark)	12% (52%)	30-50% (60-70%)
DH grid losses	20-25%	10-15%

CHAPTER 5. NEED FOR CHANGES IN DISTRICT HEATING SUPPLY

The theory of Choice Awareness says that different technically possible alternative solutions should be presented and their consequences and socioeconomic feasibility should be assessed and compared. Based on this process, a real choice can be made. In Chapter 3 and Chapter 4, the conditions under which solutions should be compared are discussed. As described, the heat sources for DH will change in the development towards 100% RE and the geographical density of heat demand will decrease in many places due to savings in existing SH demand and the development of new low-energy buildings.

In this chapter, different alternative strategies for addressing key challenges related to the future of DH are compared and discussed, between new sources on the one side, and new demands on the other. In this discussion, the two first choice awareness strategies (See subsection 2.1.2 on page 10) are handled, whereas the latter two are not addressed. Since these are also important in the development of a public choice awareness, a brief section at the end of this chapter introduces the central aspects, based on the existing literature.

5.1. EFFICIENCY, FLEXIBILITY AND SECTOR INTEGRATION

The flexibility and integration of the energy sectors are important aspects for a cost effective transition of the energy system towards 100% RE supply. As highlighted by Djørup in [72], the total costs for energy supply will not necessarily increase when moving towards a 100% RE system, but the structure of the costs will. This requires that systems are designed as smart energy systems to utilise the synergies arising from sector integration, thereby improving total system efficiency.

The efficiency of the DH supply is becoming increasingly important, as larger shares of RE and lower heating demands become prevalent. DH is still just one option among a number of individual solutions, such as HPs, electric heating or biomass boilers. If DH is not developed and improved as building efficiency and the other alternatives do, then the socioeconomic balance will tip more towards individual solutions, and it may not be feasible to connect new marginal areas to DH.

According to Connolly and Mathiesen [53], the transition towards 100% RE requires both DH and flexible HPs to integrate supply fluctuations in an efficient and cost effective way. Thermal storage in DH is needed to enable HPs and CHP to operate more independently of heat and electricity demands. A number of studies have shown the potential for HPs in integrating fluctuating renewable heat and electricity production. Pensini et al. [73] show how fuels for heating can be replaced with electricity from renewable sources by using HPs, and Ommen et al. [74] assess and compare a number of ways to integrate HPs in DH. Blarke and Dotzaur [75] suggest a new concept of integrating CHP and HP units, creating a more intermittency-friendly system. This indicates that a higher capacity of HPs will increase the ability of the system to integrate fluctuating renewable electricity sources. Blarke also, in [76], compares HPs with electric boilers in terms of cost effectiveness for that same purpose.

Even though integration of HPs seems like a good solution from a scientific and socioeconomic perspective, it is not being realised, and less than 10 MW_e is installed today in Denmark [77]. The island of Samsø, which is known for innovative solutions, is a net-exporter of RE and can be seen as a front runner on RE in Denmark, has no HPs in its DH supply, instead having a large share of biomass boiler production [78]. Likewise, for the context of Greater Copenhagen, no electric HPs have been installed. Bach et al. [79] analyse the potential for using large HPs in the DH system for this region, considering different heat sources and COP's. The results indicate that there is a potential for HPs in the region, but the authors do not conclude on economic feasibility.

One way to significantly improve the synergy between sectors and the efficiency of DH supply is by lowering the supply and return temperature set in DH networks. One benefit of this strategy is to reduce heat losses from the DH grid, but there are several other substantial benefits, which have effects beyond the supply of DH. One important benefit is an improvement of the COP of HPs used for the supply of DH. An HP's COP is determined by the temperature ranges within which it operates, where lower temperatures on the DH side and higher temperatures on the heat source side will improve the COP (see Figure 14). This provides better resource efficiency because the electricity consumption per unit of heat production decreases. It also means that a reduced DH temperature set will enable the utilisation of low temperature heat sources, which, at high DH temperatures, would not have been feasible.

In addition to reduced grid losses and COP of HPs, the efficiency of almost all other components connected to DH is improved by lowering the system's temperature set. For example, biomass boilers, waste incineration, CHP, solar thermal and geothermal plants will all operate at higher efficiencies. Due to the improved efficiencies of production units and reduced losses from the DH grids, the required capacities of the production units will also reduce, in line with lower demand peaks and lower overall utilisation. Reduced capacities will result in lower investment and maintenance costs, and improve the socioeconomic feasibility of DH.

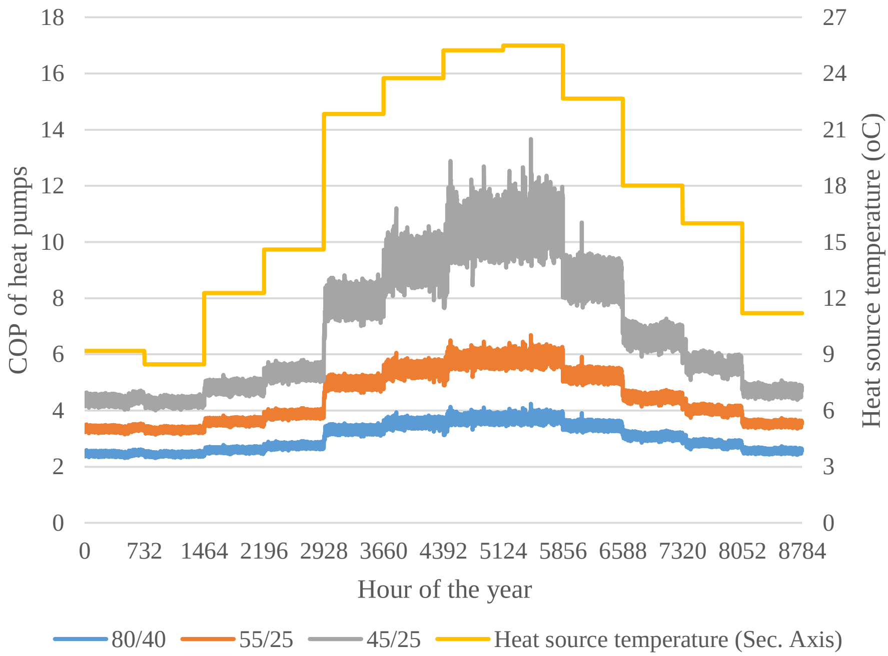

Figure 14: COP of heat pumps in three district heating temperature scenarios (80/40, 55/25 and 45/25) and the assumed heat source temperature on the secondary axis.

5.1.1. STRATEGIES FOR HEAT PUMPS AND BIOMASS (PAPER 5)

In Paper 5, short-term strategies related to the integration of RE into the DH sector in Denmark are analysed for the year 2020. The focus is on the potential for large-scale introduction of HPs and their ability to replace production from heat-only fuel boilers. In recent years, the capacity of biomass boilers for DH production is increasing due to different regulatory measures. Therefore, a special focus is put on the potential for replacing biomass consumption.

A number of scenarios introducing different capacities of HPs (25, 100, 450 and 900 MW electric capacity) in the DH systems are defined and, in parallel, it is analysed how the ability of HPs to replace biomass boilers influences the results. The results show that the 450 and 900 MW scenarios are at the same cost level, both leading to savings of 80 M€/year, but the fuel savings are 5 and 7 TWh/year, respectively. This means that HP capacities above 450 MW may not reduce the total costs further, but will reduce fuel and biomass consumption. In addition, a sensitivity analysis of fuel and electricity price development shows that the results are robust to changes in electricity and fuel price levels, with the exception of a significant increase in the electricity/fuel price-ratio, which makes it slightly costlier to invest in HPs, though this situation would still lead to a reduction in fuel and biomass consumption.

In Paper 1, a similar analysis is used to compare the MODEST and EnergyPLAN models. The results from paper 1 are very similar to those in Paper 5, even though the analysis uses a slightly different set of assumptions, and is in general less detailed. In paper 1 it is found that HPs are already feasible today and can generate a savings of 100 M€/year in 2025. The optimal capacity of HPs in Denmark is found to be between 400 – 800 MW in EnergyPLAN and 600 – 1,100 MW in MODEST.

The biggest question arising these analyses is: why has the public regulation for HPs not already been revised? An answer to that question can be found using the Choice Awareness Theory, as presented in Section 2.1. This theory states that dominant actors in a certain field will try to eliminate alternatives from the public debate to maintain their position in the field. The legislation defining the framework for the use of HPs in DH compared to the alternative of biomass boilers has consistently favoured biomass boilers [80], even though multiple studies have found that HPs can save costs for the society [33,35]. Large actors in the Danish energy sector may have been working to eliminate HPs as an alternative from the public debate; for example, via participating in the debate in the national media or by lobbying the case among parliamentarians.

The flexibility of the installed HPs is important. This includes minimum time for start-up, ability to operate part-load, ability to regulate production up and down and being able to respond to signals from the electricity system. HPs installed today are not always flexible, which reduces the benefit of their operation. Therefore, the development of HP technology for DH and the future installation of HPs should focus on their ability to operate flexibly to improve sector integration and total system efficiency.

5.1.2. SCENARIOS FOR LOW-TEMPERATURE DISTRICT HEATING (PAPER 6)

In Paper 5, discussed above, the specific temperature set of the DH systems is not considered, though a low temperature set is assumed in the IDA Scenario that forms the foundation for the study. For the HPs, fixed COPs of 3.0 and 3.5 are assumed for central and decentral DH areas. Figure 14 shows that this is a fairly good estimation, especially for the cold months. But, how does the DH temperature set influence its integration into a smart energy system, considering all the system dynamics and economic implications involved? In Paper 6, a method and an answer to this question are proposed. The effects of different DH temperature sets in the supply, distribution and consumption of DH are analysed in a systematic way to suggest how low a temperature set, in general, should be targeted when planning future DH systems.

The method is to collect data on the DH temperature set’s influence on all relevant parameters in the energy system. This includes CHP efficiency, solar thermal efficiency, HP’s COP and pipe heat losses, in addition to the costs related to the practical use of lower supply and return temperatures. For example, new radiators, valves and appliances will need to be installed in households to boost the temperature of DHW.

All the collected data is related to five different temperature sets that define the five scenarios; Heat Savings (80/40), Low Return (80/25), Low (55/25), Ultra low w. electric boosting (45/25) and Ultra low w. HP boosting (35/20). Each scenario represents a concept for DH that has different energy system and cost assumptions. The five scenarios are analysed within the context of the IDA Energy Vision scenarios for 2035 and 2050, and all analyses are performed using EnergyPLAN.

The results, seen in Figure 15, show, in general, that a temperature reduction in DH systems is a feasible strategy. A reduction of the return temperature alone, is considered feasible. This means that the necessary investments in buildings to reduce the return temperature do not pose a big risk to implementation, and, at the same time, are a prerequisite for reducing the supply temperature. Reducing the supply temperature is feasible up to a certain level, which is the lowest possible temperature without needing electricity to boost DHW. This means that no matter what technology is used for boosting the DHW temperature, this does not seem to be a feasible strategy. The investment costs associated with the necessary household investments and the increased need for electric peak load production capacity are prohibitively high.

Conventional DH components are designed for operating temperatures that are much higher than analysis shows to be the optimal level. All technical components for DH systems should be designed so they are capable of operating in low-temperature DH systems. In particular, this includes the internal building heating system (substation, radiators, valves, system monitoring and regulation), which is one of the main determining factors for enabling a low return temperature. This is a critical issue, as these will take many years to replace because they are integrated into all existing buildings.

5.2. A NEW FRAMEWORK FOR ENERGY MARKETS

A central aspect of the transition towards 100% RE is to develop the economic framework for energy markets to be able to cope with the nature of fluctuating RE sources. In [72], Djørup discusses how the increasing amounts of fluctuating RE sources are challenging the existing energy markets, which are based on short-term marginal production costs. Two related political challenges are highlighted:

1) To develop institutional structures to secure long-term economic sustainability of the energy system
2) To develop a framework for socioeconomic cost assessment of energy systems that is not based on short-term marginal production costs

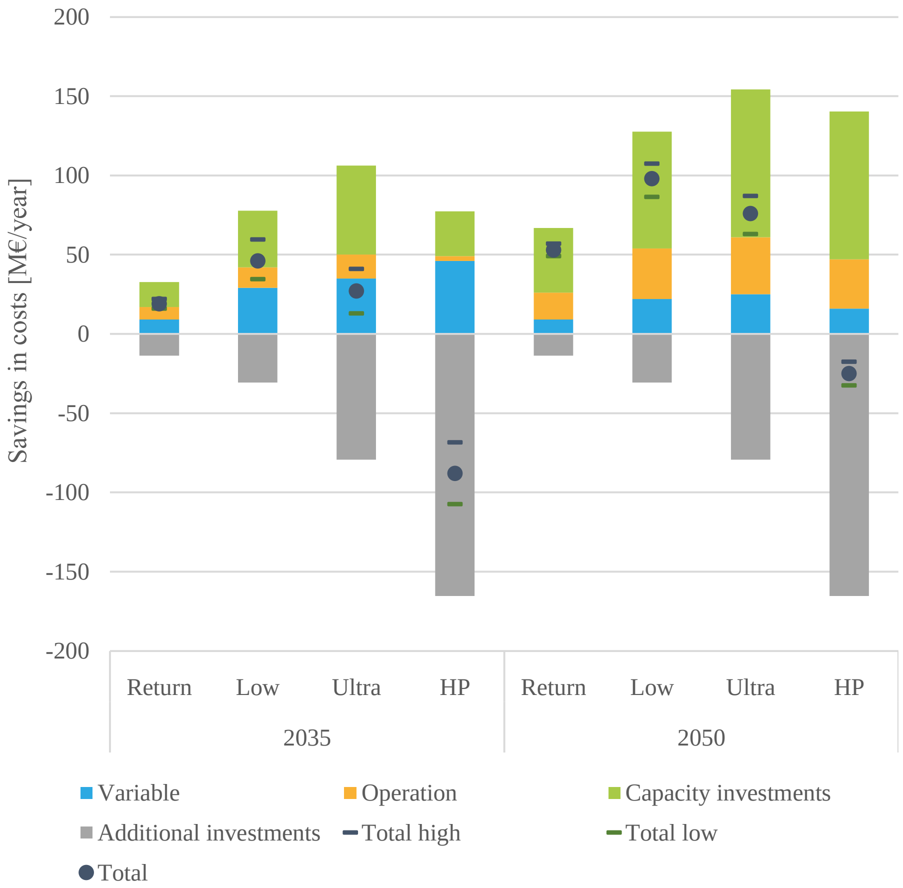

Figure 15: Savings in total costs separated into Variable costs, Operation and maintenance costs and Investment costs, for the four alternative scenarios relative to the Heat Savings scenario for 2035 and 2050. The sensitivity of the results shows the fuel price's influence on the results where Total high indicates a 50% increase and Total low indicates a 50% reduction of fuel costs.

Djørup further elaborates that in systems with high shares of fluctuating RE, the short-term marginal production cost market is not sufficient or sustainable in the long-term because the cost structure of energy production will change from being based primarily on variable production costs to a system based mainly on costs for investments in production capacity. One possible solution could be to reform the current energy market design. This could be done by supplementing the current Nord Pool Electricity market, (which is an energy market based on marginal production costs bidding) with a market for available capacity. During the transition towards 100% RE, such a capacity market would be expected to gradually include a larger share of the total costs compared to the energy market [72].

The consequences of the current energy market's flaws, mainly concerning electricity, can already be seen today, as decentral CHP plants in Denmark have fewer and fewer operational hours due to low electricity prices [81,82], even though the capacity of decentral CHP has proven to be an efficient way to integrate wind power [81,83,84]. In this connection, Sorknæs et al. analyses the ability of decentral CHP plants to improve their feasibility by participating in electricity balancing tasks [82]. This is concluded to have a positive effect, though it might not be enough for the plants to survive under the current market conditions. Sorknæs et al. also mentions a capacity market as a possible solution to keep decentral CHP plants online, thereby contributing to the flexibility and integration of the energy sectors.

5.3. SUMMARY

A number of changes are needed to enable the development of a 4th generation DH supply system to overcome the challenges of the current conventional way of supplying DH. A fundamental issue is the economic conditions for the energy sector as a whole, and for DH in particular. A new organisation and economic framework will have to be introduced to secure the development towards a long-term feasible and sustainable system.

The two central aspects of the development of the DH supply systems are to improve the efficiency of DH supply and to increase the flexibility of supply through sector integration. The introduction of flexible technologies improves the system's ability to utilise a fluctuating renewable electricity supply and improves total system efficiency. Large HPs should be utilised that can flexibly consume electricity for heat production, thereby reducing the need to combust biomass and improving system flexibility and efficiency. System efficiency can also be improved by reducing heat losses from different parts of the system. One method for doing so is to lower the supply and return temperatures of DH systems. This reduces pipe losses, improves efficiency of supply units and reduces the need for peak production capacity. The main differences between the DH supply system of today and a future system is listed in Table 6.

Some of the DH supply technology will have to be improved to fit with the suggested changes in the future system. The HPs should be developed to operate more flexibly than today, to accommodate the fluctuating renewable electricity supply. The different DH system components should also be designed for use in reduced operating temperatures, particularly those components in internal building heating systems, so that they can produce low return temperatures.

Table 6: Overview of main differences between the district heating supply systems of today and in 2050.

Parameter	**Today (2015)**	**Future (2050)**
Generation of DH	2nd / 3rd	4th
Energy sector integration	Low	High
Implementation of heat pumps for DH	Demonstration level	Large-scale
Biomass-based DH production	Substantial	Limited
Total system efficiency	Medium	High
Temperature level of DH	Conventional (80/40)	Low temperature (Towards 55/25)

CHAPTER 6. CONCLUSION

This thesis presents and discusses how heating demands should be covered in future energy systems based on 100% RE, with a particular focus on DH systems and technology and the development towards 4th generation DH. The thesis is structured around three main parts: 1) new heat sources, 2) reductions in heat demands and 3) changes in the supply system. The research question is concretised into three sub-questions, to which these three parts correspond.

The case for the analyses is Denmark, but the conclusions do not exclusively apply to Denmark. There are large similarities between the countries in Europe, which have been identified in the Heat Roadmap Europe studies. The basic heating and cooling demands are not very different across Europe. Today, the energy systems might be very different between different countries, but in the long term, e.g. 2050, large parts of the infrastructure will have to be replaced, and in this context, radically different solutions can be considered.

- *Which heat sources for DH should be considered in RE system?*

In Denmark, heat production from CHP, fuel boilers and waste incineration make up more than 90% of the total current heat production; but, according to the IDA Scenario, this should drop to about 30% in 2050. Central CHP plants, from which 40% of today's production is supplied, will produce much less heat in the future; however, they will play a more central role in the supply of electricity, and they should therefore be very flexible in their ability to regulate, e.g. as CCGT plants are. To replace these in the heat sector, new heat sources based on RE will have to be introduced on a large scale. In this sense, electric HPs will have a central role to play, with about 30% of the total production. It has been found that heat sources for HPs exist on the same order of magnitude as suggested in the IDA Scenario, though the geographical distribution is not proportional to demand. This means that less efficient heat sources will have to be utilised in areas with large demands. In addition to HPs, industrial excess, solar thermal and geothermal heat will have to contribute significantly more to total production in the future to keep the consumption of biomass at a sustainable level.

- *How much will and should heat demands be reduced in the future?*

The need for DH production to cover heat demands can be divided into three parts: 1) space heating (60%), 2) domestic hot water demand (20%) and 3) heat losses in the distribution grid (20%). In this thesis, potential savings in space heating and grid losses are considered. Savings in space heating have been covered extensively in the literature, and the results show that 30-50% reductions are feasible in Europe. Considering potential savings in grid losses from an energy systems perspective, it is found that a 29% reduction of the current heat loss (Series 3 pipes) is the most socioeconomically feasible option. A reduction of 44% (Series 4 pipes) can reduce the fuel consumption further, but has higher costs, which means that the scarcity of biomass will be a determining factor.

- *How should DH supply and technology change to fit the new conditions?*

The DH supply should change in a number of ways, but with two central purposes: to improve the efficiency and to increase the flexibility of supply. Flexibility is needed to balance supply and demand in systems with large amounts of fluctuating RE. Electric HPs have a central role here because they consume electricity and produce DH, which improves the integration of the electricity and heating sectors, and thereby increases overall flexibility. An assessment of the potential for the integration of HPs into the Danish energy system shows that a capacity of between 450 and 900 MW_e will already be feasible by 2020, which is similar to the capacities assumed in the IDA Scenarios. Such capacity would reduce fuel consumption by 5 to 7 TWh/year, which can be compared to the marginal biomass potential in Denmark of 66 TWh/year [33].

HPs also have an important role in improving system efficiency, since they allow for the utilisation of low temperature heat sources at a high efficiency. In an assessment of different alternative DH concepts with a focus on temperature level, increased HP efficiency is found as one of the biggest benefits of reducing the DH temperature level. The study concludes that the DH temperature set should be reduced as much as possible, until reaching the point at which the temperature of DHW must be boosted locally in the buildings using electricity, because that would require prohibitively large investments in the buildings' heating systems as well as the supply system. The preferred temperature set is found to be 55/25ºC, with a socioeconomic benefit of 100 M€/year by 2050 in Denmark.

Some improvements in the technology used for DH supply will have to be developed in the process towards 2050. Power and CHP plants should be designed to be flexible in operation, be able to regulate fluctuations in production from RE, and have a high electric efficiency. To make full use of HPs' potential, the technology related to heat source intake, operation within different temperature ranges and operational flexibility should be improved. In general, the design of all DH components should be prepared for low-temperature operation to make it easier to reduce DH temperatures at a later stage. Particularly, the building heating systems should be prepared for low-temperature operation.

To realise these changes in the Danish context, the framework for DH production and supply will have to be revised. This includes changes in the taxation and regulation of DH producers and, over the longer term, a reform of the way in which electricity is traded, because these currently constitute barriers to the long-term and sustainable transition of the energy system towards 100% RE energy supply.

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APPENDICES

PAPER 1

Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark

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Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark

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ABSTRACT

Denmark has a national political goal of a 100% renewable energy supply in 2050. This requires a comprehensive transition of the energy system. For some decades, district heating in Denmark has been contributing to high fuel efficiency as well as to the integration of the electricity and heating sectors. Large-scale compression heat pumps would improve the integration between the district heating and power sectors by utilising the fluctuations in the supply from wind power, solar photo voltaic and other sources. Previous studies indicate that the introduction of heat pumps in Denmark will have a positive impact on the total costs for energy supply in the transition towards 100% renewable energy. In this paper, this is further investigated to assess the feasibility of heat pumps in the Danish energy system. The assessment is made by applying two different energy system analysis tools, named EnergyPLAN and MODEST. The comparison and discussion of these tools is a secondary purpose of the study. In general, the results show a potential for introducing heat pumps in Denmark between 2 and 4 GW-thermal power and a total potential benefit around 100 M€/year in 2025.

1. Introduction

The national political goal for the Danish energy system is to have a 100% renewable energy (RE) supply in 2050 (The Danish Government, 2012). This involves a transformation of the existing energy system, which is at present supplied with approximately 73% fossil based energy (Danish Energy Agency, 2015a). Currently, the transition is challenged by extraordinary low electricity prices, which reduce the short-term feasibility of wind turbines and the incentive to invest in new turbines. The low electricity prices also limit the operation of combined heat and power (CHP) plants in district heating (DH) systems. Hence, CHP is replaced with heat production in biomass based heat-only boilers and the incentive to reinvest in CHP capacity is small. This is reflected in the Danish transmission system operator's projection of the CHP capacity in Denmark, which is expected to decrease significantly during the coming decades. See Fig. 1.

This development will reduce the general fuel efficiency of the energy supply in Denmark and heat pumps (HPs) are often suggested as a solution to this. HPs can increase demand for electricity and produce heating at a high efficiency replacing production in heat-only boilers. HPs are generally not a feasible technology for the DH plants to invest in because of the current tax structure. It will require a revision of the regulatory framework for HPs in DH to become feasible. In the neighbour countries Sweden, Norway and Finland, which have similar conditions as Denmark, there are already large HPs operating in DH. In (Clausen et al., 2014) a number of examples are given from these countries above 10 MW-scale per plant, and using different heat sources.

1.1. Related studies

In the transition towards 100% RE, the biomass used for energy supply is an increasingly critical resource, as it is the only naturally available fuel that can directly substitute fossil fuels. Hence, the biomass resources used in energy systems should be prioritised for purposes where fuel is needed or for process energy where other options are not viable. This is discussed further in (Mathiesen et al., 2012). Andersen and Lund (2007) present one solution to strengthen the position of CHP plants by establishing new

List of abbreviations: CHP, Combined heat and power; COP, coefficient of performance; DH, District heating; HP(s), heat pump(s); RE, renewable energy.

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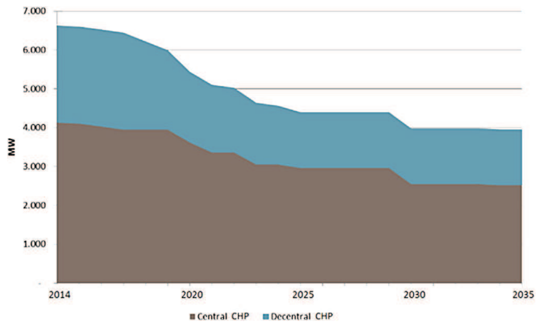

Fig. 1. Projected development in CHP capacity in Denmark for central and decentralised CHP plants (Energinet.dk, 2015).

partnerships between decentralised CHP plants. Thereby, the plants become able to deliver new electricity system services by cooperating on bidding in the electricity markets. Karschin and Geldermann (2015) also focus on the fuel efficiency of using CHP for heat production recognising the availability of biomass resources as a parameter in planning for systems based on RE.

According to Connolly and Mathiesen (2014), the development towards a 100% RE system requires a combination of DH and flexible HPs to integrate the fluctuating energy sources in the most feasible way. Thermal storage in the DH system is needed to allow HPs and CHP to operate more independent of heat demand and electricity prices. As larger capacities of fluctuating power supply is introduced, other storage technologies may be needed as well. Even the island of Samsø, which is known for innovative solutions; is a net-exporter of RE and can be seen as a front runner on RE in Denmark, has no HPs in its DH supply, but a large share of biomass boiler production (Nielsen and Jørgensen, 2015). For the context of Greater Copenhagen, Bach et al. (2016) have analysed the potential for using large HPs in the DH supply, considering different heat sources and COP's. The results indicate that there is a potential for HPs in the region but do not conclude on overall feasibility.

A number of studies have shown that HPs have a potential for integrating fluctuating renewable heat and electricity production. Pensini et al. (2014) show how fuels for heating can be replaced with electricity from renewable sources by using HPs. Ommen et al. (2014) suggest and assess a number of specific ways of integrating HPs in DH. Blarke and Dotzauer (2011) suggest a new concept of integrating CHP and HP units creating a more intermittency-friendly system. This indicates that a higher capacity of HPs will increase the ability of the system to integrate fluctuating renewable electricity sources. In Blarke (2012), HPs are compared with electric boilers in terms of cost effectiveness for that same purpose.

1.2. Contribution of the present study

The purpose of this study is two-fold. The primary purpose is to assess the economic potential for introducing HPs in DH in Denmark. The secondary purpose is to compare and assess the differences of two types of tools for performing the analysis. This is done by developing energy system models for the Danish energy system in 2013 and 2025, respectively, and identifying the economically optimal capacities of HPs in these models. This analysis is done in two different energy systems analysis tools, EnergyPLAN and MODEST, and the results and differences are compared and discussed. The knowledge produced can support political decisions on the energy system development in Denmark.

Chapter 2 presents central theoretical considerations and methods regarding the energy systems modelling followed by Chapter 3, which presents the concrete applied analysis assumptions. In Chapter 4 the results of the analysis is discussed and in Chapter 5, conclusions are given.

2. Theory and methods

In this chapter, the main theoretical concepts and background for the choice of the modelling tools are elaborated.

2.1. A system approach

To apply a system approach is a way of thinking (Churchman, 1968) about the total studied system and its components. According to Wallén (1996), a wide definition describes a system as a group of objects that interact. As a totality, the system has qualities which are more diverse than what can be expected in the single objects. Also Ingelstam (2002) claims that a system entails two types of parameters: the components of the system and the connection between them. In system analyses, it is vital to identify the connections between the different components of the system and the interaction between them as well as to interpret the system itself.

When conducting a system analysis, the first assignment is to find an appropriate delimitation: what is inside and what is outside the system. In addition to system delimitation, some of the main points in theoretical system analyses are the creation of a system and studies of, for example, energy flows inside the system and flows between the system and the surroundings; connections between the different parts of the system, and how the system alters over time (Wallén, 1996).

2.2. Theory of energy system analysis

Energy systems can be seen as networks connecting sources of energy with end-use demands through various conversion and storage technologies and energy grids transporting the different types of energy.

Energy system analysis tools are computation tools to structure and simplify the complexity of the real energy systems in models describing the energy sources, conversion technologies, energy flows, etc., in a systematic way. The model forms the basis for making analyses of issues related to the modelled system.

The modelling is the process of establishing the framework and a starting point for the analysis. This can include the definition of available energy sources, capacities of conversion and storage technologies and energy demands. The analysis is the way in which the computation tool handles the data in the model together with possible analysis parameters. The combination of these two and the possible analysis outputs makes the tool fit a specific type of application. See Fig. 2.

Lund points out in (Lund, 2014) that all energy system analysis tools are developed with a specific purpose and with the ability to handle a specific type of energy systems and analysis questions. It is important to be aware of this when choosing a tool for analysis. Hence, some tools might be used for an analysis that answers a question outside the scope and purpose of the tool, which might generate misleading results.

2.3. Choice of energy system analysis tools

Since the purpose of this study is to investigate the potential for introducing large-scale HPs in DH in Denmark, where the electricity production from wind and solar is expected soon to reach

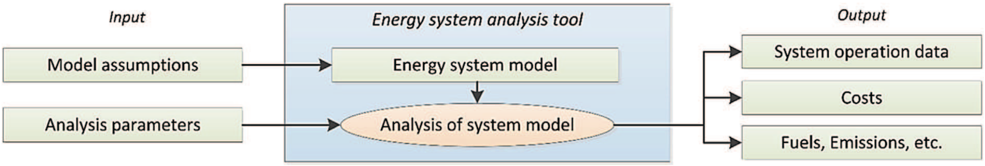

Fig. 2. Conceptual diagram of energy system analysis tool with inputs and possible outputs.

50% of the demand, the analysis tools should be suited for this application.

Lund discusses in (Lund, 2014) two main challenges of modelling and analysing energy systems with large shares of fluctuating and intermittent energy sources. The first challenge is handling the fluctuations in a way that reflects the dynamic behaviour of the energy system and the interaction between the components of the system. The other challenge is limiting the biomass consumption to a sustainable level in the development towards an energy system based on 100% RE.

Segurado et al. (2009) compare a number of energy systems analysis tools in terms of a series of chosen parameters. This includes types of database availability and abilities to perform cost and environmental analyses. A similar approach is applied by Connolly et al., who review 37 different energy system analysis tools and divide the tools according to a number of parameters relevant to the analysis of integration of RE (Connolly et al., 2010). Following Connolly's arguments, a number of requirements to the tool can be extracted for this study:

1) Handling of a national energy system
2) Analyse large-scale integration of fluctuating RE sources
3) Model the integration of DH and electricity sectors
4) Calculate system costs
5) Presenting detailed computational data of the model analyses

Lund argues in (Lund, 2014) that 100% RE systems should be modelled taking into account the variation from hour to hour in the energy system to capture the dynamics in the system properly. In a system with only a small share of fluctuating RE, it may be sufficient to make a calculation without account for hourly variations. However, with 50% electricity supplied from wind and solar power, this case can be regarded as large-scale integration, which according to Lund requires an hourly calculation.

Following the discussion of the requirements to tools for the stated purpose in this chapter, the two tools EnergyPLAN and MODEST have been chosen. These tools can be seen as complementary as EnergyPLAN has a high temporal resolution, whereas MODEST performs a numerical optimisation. Individually, both tools are suitable for the given purpose, but at the same time the tools perform differently in the analysis. This gives an opportunity for the comparison of results and an assessment of the sensitivity of the results to the choice of tool type.

2.4. The EnergyPLAN tool

EnergyPLAN is designed to model and analyse the large-scale integration of RE and 100% RE systems. EnergyPLAN has an inbuilt model of an energy system, defining the possible energy source, conversion units, demands, etc., and the flows between them. This is a very thorough model enabling analyses of many different types of technologies and energy sources, but the user cannot define new types of conversion units that do not already exist in the model. The user has to provide inputs in the form of installed output capacities, efficiencies, fuel mix, costs and demands.

It can be defined in the model how the system should optimise and which solutions should be given priority. The optimisation is based on analytical programming, which means that the optimisation strategies are based on a predefined merit order of the technologies based on the resource efficiency of the technologies and the lowest marginal operation costs, among others. This means that the system does not seek to find an optimal solution as such, but rather simulates how the system operates under given priorities.

The tool works on an aggregated level in the sense that not every plant is modelled, but all plants of the same type are modelled as one. This enables the tool to model and analyse national energy systems in a way that is not too time consuming, as in Connolly and Mathiesen (2014) where the energy system of Ireland is analysed. The tool is able to model the large-scale integration of RE by the use of a variety of technologies for conversion between different forms of energy (electricity, heat, gas, hydrogen, etc.). This enables the tool to integrate the energy sectors, for example CHP plants, HPs, electric boilers, electrolysis plants and electric vehicles. These are modelled on an hourly basis to take into account the fluctuations in the production and demands and to enable the storage between energy sectors. This is described under the "Smart Energy Systems" concept in the review article in Mathiesen et al. (2015a).

In EnergyPLAN, the annual system costs can be calculated, which include annuity of investments, fixed and variable costs and fuel costs. The tool does not include a dedicated investment optimisation function, but the optimal capacity of, e.g., HPs can be found in an iterative process manually changing the capacity, thus reaching a minimum of total system costs. Furthermore, the tool provides very detailed results of the calculations, at hourly resolution if needed and for all system flows. This makes the results transparent and it makes the review of the details of a certain simulation very easy.

2.5. The MODEST tool

MODEST is a tool for the optimisation of dynamic energy systems with time-dependent components and boundary conditions. General input data that need to be defined when building a model in MODEST are studied period, time division, discount rate and the energy demands that must be fulfilled (e.g. heat, biofuel, electricity, cooling). Besides the demand nodes, the other elements in the model are networks, plants, start nodes (such as fuels), and so-called "waste nodes". These "waste nodes" open up possibilities for producing more electricity for purposes of export, producing excess heat in order to increase the electricity production, or even producing other by-products (e.g. biofuels or pellets). The plants in the model are described in terms of their efficiencies, maximum capacity, power-to-heat ratio (if it is a CHP plant), maintenance periods and costs, technical and economic lifespans, and possible investment cost (Gebremedhin, 2003; Henning, 1999).

The aim of the optimisation is to minimise the system cost of supplying the defined energy demands during the analysed period. The system cost includes: new investments, operation and maintenance costs, fuel costs including taxes and fees, as well as revenues from by-products, and lastly, the present value of all the capital costs. The optimisation is performed by choosing the best operation at each time period from existing and potential new plants in the system. Besides the system costs, other outputs from the tool are, e.g., detailed data about the fuel and electricity use, detailed data about productions from the plants and data related to delivering through the networks.

During the last 20 years, MODEST has been applied to different kinds of energy systems with different purposes. In most of these studies, a time division where each year is divided into 88 periods is used. This time division is developed in order to depict seasonal, weekly and diurnal variations in the heat demand and electricity prices. The time division is described in more detail in (Henning et al., 2006). However, a new distribution of hours has been made for this analysis to better reflect the fluctuations in the wind power production. This time division consists of 96 periods. Every month, hours are divided into the following eight "groups" of hours:

- Monday–Friday 8–13
- Monday–Friday 13–18
- Monday–Friday 18–22
- Monday–Friday 22–8
- Saturday, Sunday and Holidays 8–22
- Saturday, Sunday and Holidays 22–8
- High wind (72 highest hours)
- Low wind (144 lowest hours)

Here, it is emphasised that the hours with extreme wind conditions, either high or low, will be handled individually. This improves the system sensitivity to fluctuations in the wind production.

3. Modelling assumptions and input data

In this chapter, the structure of the research performed for this study is described and the applied assumptions and inputs data are presented.

3.1. Model of the energy system in Denmark

The model of the Danish energy system used in this study is shown in Fig. 3. The nodes and flows defining the models are described using a number of parameters and characteristics, such as annual production, efficiencies, conversion capacities, costs, etc., which differ between the scenarios. These specific assumptions are presented in Section 3.3. However, the general system of nodes and flows, shown in Fig. 3, is the same in all scenarios and analyses.

The model is structured according to three DH groups which represent different types of DH systems. The DH groups are defined as follows:

DH Group 1) Decentralised DH systems without CHP units
DH Group 2) Decentralised DH systems with back pressure CHP units
DH Group 3) Centralised DH systems with extraction CHP plants

The three groups are included to take into account the differences in heat sources and possibilities of interaction with the electricity system. These differences create different potentials for the integration of HPs and electric boilers. The results, presented in Section 4, are not divided into DH Groups, but the details can be found in Appendix.

3.2. Scenarios

The two scenario years for the study have been chosen, 2013 and 2025, to be able to conclude on the current and near future potential for introduction of heat pumps in DH.

3.2.1. Energy system assumptions

The parameters in the scenario related to the year 2013 are based on statistical data for the year 2013 (Danish Energy Agency, 2014a). The year 2013 has been chosen because this was the latest year where all needed data for the modelling were available. This scenario is documented further in connection to the project IDA Climate Vision in Mathiesen et al. (2015b) and is used as a point of reference when the 2025 scenario is discussed. The scenario for 2025 is based on the statistical data for 2013 combined with a projection of the DH and power sector development made by the Danish Energy Agency (2014b).

In Table 1, the main energy system parameters are presented.

3.2.2. Cost assumptions

The system costs are calculated as socioeconomic costs, which include investments, operation and maintenance, fuel, electricity import and export. System costs do not include taxes, subsidies or levies, because these represent a redistribution of costs rather than actual costs. The term *feasible* is used in this paper to say that something has a positive socioeconomic contribution. The main cost assumptions included in the study are presented in Table 2. The energy prices for the 2013 scenario are based on statistics from the Danish Energy Agency (Danish Energy Agency, 2013) and those for 2025 are from the fuel price prediction in Danish Energy Agency (2014b). Technology investment costs are from "Technology Data for Energy Plants" (Danish Energy Agency, 2015b). A socioeconomic discount rate of 3% is applied for the investment costs (Dyrelund et al., 2010). Investment costs for included technologies not mentioned in Table 2, fixed and variable operation costs and technical investment lifetime are included in the calculations, but not presented here since these have a minor influence on the results. These can be found in the references as presented above.

3.3. Analysis procedure and sensitivity analysis

The analysis consists of a number of calculations using the two tools, where key parameters are altered to enable the assessment of the sensitivity of the results to these parameters. For every time a parameter is altered, the optimal capacity of HPs is found corresponding to the minimum total system costs – referred to as the potential. Electric boilers are included in the calculations as an option as well.

Baseline calculations. Initially the scenarios are calculated in both of the tools without any HP capacities as a point of reference.

Closed system calculations. The closed systems are without any electricity import/export capacity to neighbouring regions. The purpose of these calculations is to compare the operation of the model in the two different tools. This configuration is also used in the calibration of the model in the two tools.

Electricity and fuel prices. The electricity and fuel price levels can have a significant impact on the feasibility of HPs because of the markets in which the HPs compete, i.e. DH production and electricity consumption. In this analysis, the price levels are each increased and reduced by 33%. See the assumed values in Table 3.

Investment costs and coefficient of performance (COP) of HPs. The investment costs and COP of the HPs are both related the technological development and the choice of heat source for the HPs. The COP of the HPs is related to the temperature level in both the heat source and the DH networks. No specific temperature

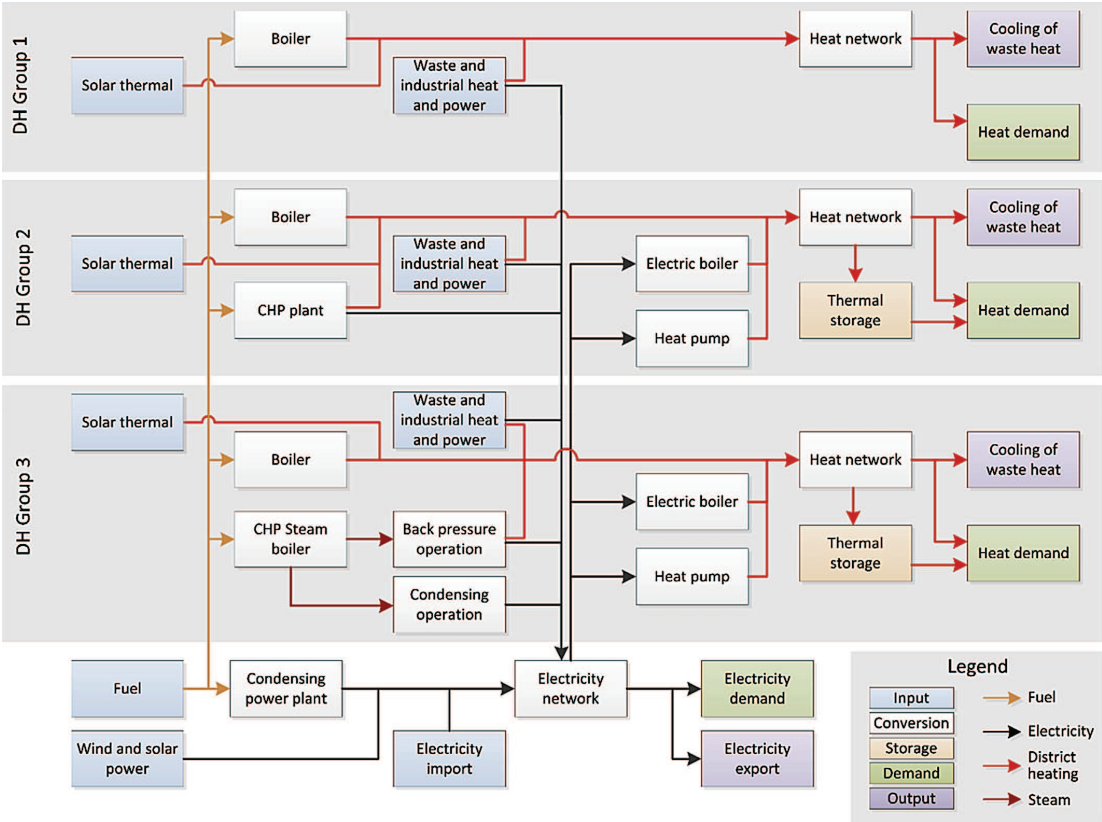

Fig. 3. Schematic diagram showing the model of the energy system for Denmark implemented in the analysis tools. The DH (District heating) groups 1–3 refer to the interaction with the electricity grid. (1. DH without CHP, 2. DH with back pressure CHP and 3. DH with extraction CHP).

levels are considered in this study, but the assumed COP is representing a mix of DH networks and heat sources with different temperature levels. In the future, if temperature levels in general are reduced, the COPs will increase. The investment cost is changed with+/-33% in the analysis and the achievable average COP is changed with+/-0.5. The applied values are shown in Table 4.

4. Results and discussion

In the first part of this chapter the results of the analysis of the feasible HP capacities in Denmark applying the base line assumptions are presented. In the second section, the main uncertainties related to external conditions and modelling assumptions are presented and discussed. Detailed operational output data for the calculations from the two tools can be found in the Appendix.

4.1. Feasibility and potential of heat pumps

In Fig. 4, the main results are presented for the two scenarios. The *Reference* scenarios show the total system costs of the systems without any HP or electric boiler capacities. The *Potential* scenarios show the costs of operating a system with optimal capacities.

It can be seen that MODEST identifies higher HP capacities and slightly higher total system costs than EnergyPLAN, but in the same order of magnitude. It can also be seen that both tools find a socioeconomic potential for introducing HPs in both of the scenarios and that the potential in 2025 is significantly higher than in 2013. The socioeconomic benefit of investing in the optimal HP capacity is about 100 M€/year in 2025, considering the reduced costs in the system. See Table 5 in the Appendix for more details.

Fig. 5 shows the results of the closed system analysis. Here, it can be seen that the costs are higher when electricity trade is not included but also that the differences between MODEST and EnergyPLAN results are minor. It can also be seen that the escalation in the feasible HP capacity, from 2013 to 2025, is about halved in the closed system analysis, which means that the HP capacity is sensitive to electricity market conditions.

The diagram in Fig. 6 shows the relation between HP capacity and total system costs for the 2025 scenario both for base line and closed system calculations. Here, the optimal values seen in Figs. 4 and 5 are indicated with circles in the graphs. It can be seen that the tendencies in the results are similar for the two tools both for base line and closed system calculations. The costs identified by MODEST are generally higher than for EnergyPLAN, 0.02–0.12 B€/year, but the tendencies are similar and the tools identify optimal capacities in the same order of magnitude.

Table 1
Main energy system parameters for the two analysed scenarios; 2013 and 2025. The DH (District heating) groups 1–3 refer to the interaction with the electricity grid. (1. DH without CHP, 2. DH with back pressure CHP and 3. DH with extraction CHP) (Danish Energy Agency, 2014a, 2014b).

Parameter	Unit	2013	2025
Electricity			
Electricity demand	TWh/year	34.22	36.93
Wind power production	TWh/year	11.12	19.91
Solar PV production	TWh/year	0.52	3.06
Waste and industrial power production	TWh/year	3.59	3.59
Condensing power capacity	MW	6244	4890
Import/export capacity	MW	5450	8765
DH group 1			
Heat demand	TWh/year	2.7	2.7
Heat loss	%	0.2	0.2
Waste and industrial heat production	TWh/year	0.91	0.91
DH group 2			
Heat demand	TWh/year	8.5	8.4
Heat loss	%	0.2	0.2
Waste and industrial heat production	TWh/year	1.95	1.95
Solar thermal production	TWh/year	0.14	1.0
CHP capacity	MW-e	1889	1541
CHP electric efficiency	%	0.36	0.36
CHP thermal efficiency	%	0.4	0.4
Thermal storage capacity	GWh	33.2	33.2
DH group 3			
Heat demand	TWh/year	19.4	19.2
Heat loss	%	0.15	0.15
Waste and industrial heat production	TWh/year	3.82	3.82
Solar thermal production	TWh/year	0	0.3
CHP capacity	MW-e	4852	3800
CHP electric efficiency	%	0.31	0.31
CHP thermal efficiency	%	0.45	0.45
Thermal storage capacity	GWh	15.7	15.7

Table 2
Main economic assumptions for the two analysed scenarios; 2013 and 2025.[1] The hourly price distribution of 2013 is scaled to the given level for 2025.

Parameter	Unit	2013	2025
Energy prices			
Coal	€/GJ	3.1	3.3
Oil	€/GJ	15.0	18.7
Natural gas	€/GJ	9.1	9.6
Biomass	€/GJ	7.3	8.1
Electricity price (year average)	€/MWh	38.0	45.0[1]
Investment costs			
Large-scale HPs	M€/MW-th	2.5	1.8
Electric boiler	M€/MW-e	0.1	0.1

Table 3
Assumed data for electricity and fuel price levels in the baseline, high and low configurations.

(€/MWh)	Electricity (average)	Coal	Oil	Natural gas	Biomass
Baseline assumption	45.0	11.9	67.4	34.4	29.3
High value	60.0	15.8	89.6	45.8	39.0
Low value	30.0	7.9	44.9	22.9	19.5

Table 4
Assumed values for the heat pump technology parameters; investment cost and COP for the baseline, high and low configurations.

	Investment cost (€/MW-th)	COP
Baseline assumption	600,000	3.0
High value	800,000	3.5
Low value	400,000	2.5

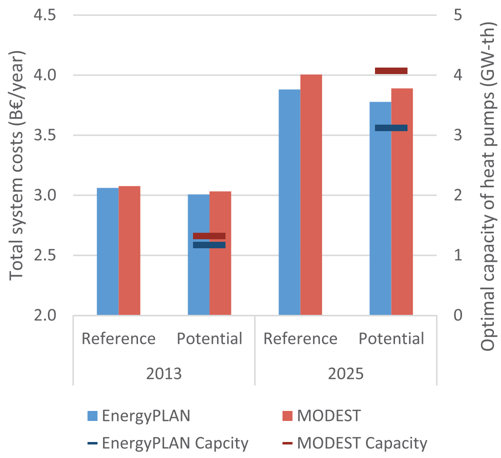

Fig. 4. Main results of the two scenarios, 2013 and 2025, showing the optimal heat pump capacities in the calculation of the heat pump potential and the total system costs. Line markers indicate optimal capacity of heat pumps.

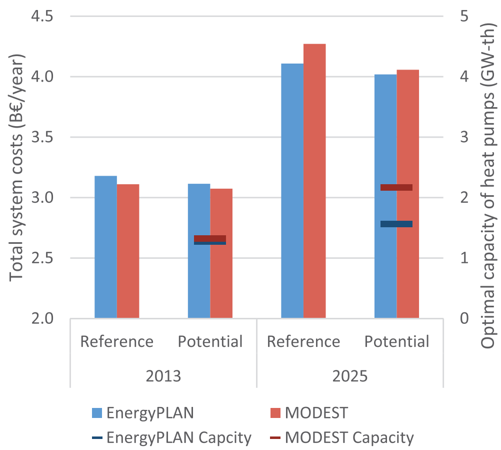

Fig. 5. Results of a closed system analysis (excluding electricity exchange) for the two scenarios, 2013 and 2025, showing the optimal heat pump capacities in the calculation of the heat pump potential. Line markers indicate optimal capacity of heat pumps.

4.2. Sensitivity to changes in assumptions and modelling

The results of the main sensitivity analyses are presented in Fig. 7. Here, the consequences of applying alternative high and low values of central analysis parameters, can be seen. More details in Table 6 in the Appendix.

Changes in the electricity and fuel price levels both show relatively high sensitivity, because the optimal capacity goes from more than 5 GW to almost 0 GW. It is important to notice that it is the relative change between the electricity and fuel prices that is important, because in the two cases, the supply of DH shifts from being mainly based on electricity (by HPs) to being based on the combustion of fuels. This means that if, for example, both fuel and electricity prices follow a similar development trend, either increasing or decreasing, the optimal capacity of HPs will not

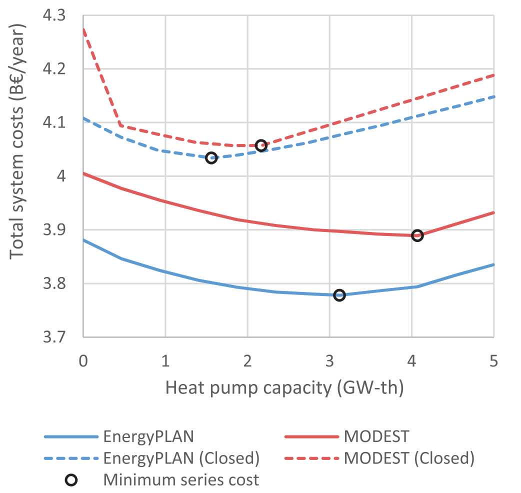

Fig. 6. Trends in total system costs in the 2025 scenario with increasing heat pump capacity; for the base line calculations and for closed system calculations.

change significantly.

The results are less sensitive to changes in the investment costs and the COP of the HPs. This can be seen as the optimal HP capacities differ less than changes in the energy prices. This means that no matter if the investment costs of HPs decrease and no matter if an average COP of only 2.5 can be obtained, a capacity of around 1.0 GW is still feasible.

The results of four central sensitivity analyses are presented, but the sensitivity to other variables have been tested in connection with this study as well. This includes CO_2-emission costs, discount rate of investments and wind power penetration. However, none of the other tested variable showed remarkable sensitivity, and are therefore not included in this paper. Other central assumptions are discussed in the following section.

4.3. Discussion

In this study, it has been assumed that heat sources for HPs are available at unlimited capacities whenever needed for heat production, but the heat sources may in reality be a limiting factor to the possible capacities. Lund and Persson have in (Lund and Persson, 2016) mapped eight different potential heat sources for large HPs in DH. They conclude that heat sources are available in nearly 99% of all DH networks in Denmark without quantifying the time dependency of the heat source capacity. This indicates that it might be possible to achieve heat sources for large capacities of HPs, but the changes in the heat sources during the year should be analysed to determine the annual changes in potential capacity and COP.

As discussed in Section 2.3, Lund (2014) argues that the modelling of energy systems with a large integration of fluctuating RE sources should be performed using at least an hourly temporal resolution. This is in order to provide a sufficient representation of the fluctuations and the impact of these on the energy system. This study shows, on the other hand, that an analysis using only 96 time divisions in MODEST, compared to 8784 in EnergyPLAN, produces very similar results of system operation, fuel consumption and costs. This indicates that hourly modelling may not be necessary at large-scale integration. 100% RE systems with large-scale energy storage will likely have a higher need for detailed temporal modelling and up to 99 time divisions may not be sufficient in this case, but that is not analysed here.

Denmark is not the only country with a large interest in wind power. Most of Denmark's neighbouring countries are also building wind farms with increasing sizes. Europe's largest onshore wind farm of 1 GW has recently been announced for construction in Norway (Statkraft, 2016) and the world's biggest offshore wind

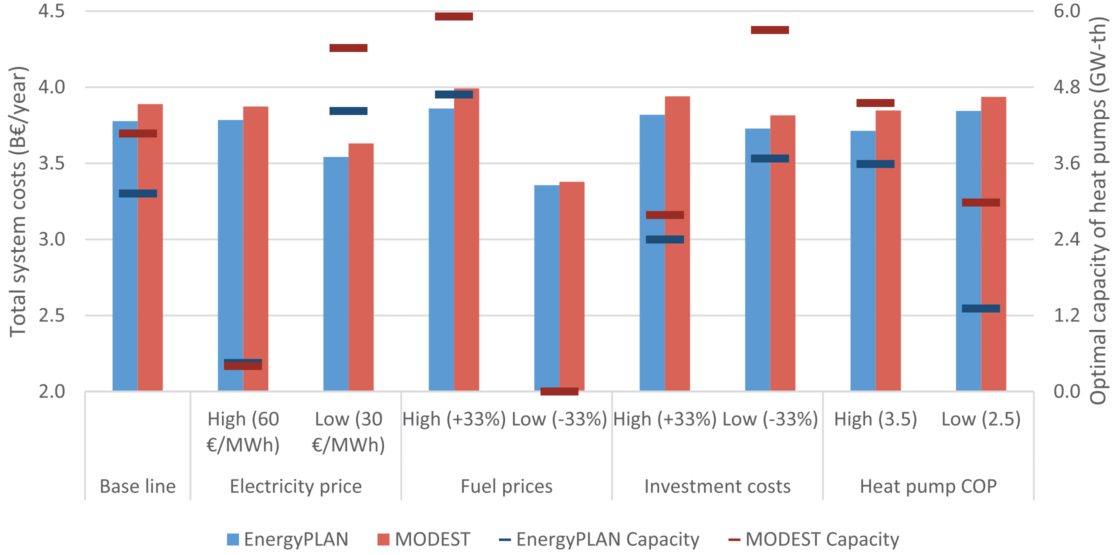

Fig. 7. Diagram showing the sensitivity of the results to a number of central analysis parameters in the 2025 scenario. Line markers indicate optimal capacity of heat pumps.

farm of 1.2 GW has also recently been announced for construction in the UK (DONG Energy, 2016). This means that the economic potential for import and export of electricity will be limited because of the similarities in weather patterns in different countries. Rodríguez et al. (2014) have analysed how electricity interconnection affects the integration of 100% fluctuating renewables in Europe and found that the need for back-up power can only be reduced from 24 to 15% from no interconnection to a fully-interconnected Europe. Similarly, Østergaard (2008) found that the effect of interconnection between countries with high wind power penetration is limited, taking into account the temporal difference in the occurrence of the fluctuations. This is important to keep in mind because, as shown in this analysis, HP capacities above 2 GW of thermal power will be dependent on external electricity trade. The capacity of 2 GW found in the closed system analysis shows only the potential for the Danish energy system, whereas the 4 GW found in the base line analysis depends on the trade of electricity at the assumed price level. The 4 GW can therefore be seen as a good level, according to an optimistic perspective on the development of the energy price levels, whereas the 2 GW found in the closed system analysis can be seen as a conservative level of HP capacity in Denmark.

On the basis of the results, it can be recommended to revise the current public regulation related to the business economy of HPs in DH. This is necessary because the current public regulation does not encourage investments in HPs for DH, and that is a barrier to the realisation of the socioeconomic potential shown in this study.

5. Conclusions

The study shows that there is a socioeconomic potential for introducing HPs in DH in Denmark already today of up to 50 M€/year and increasing to 100 M€/year towards 2025. The optimal capacity appear to be in the range between 2 and 4 GW of thermal power. The application and results of the two tools EnergyPLAN and MODEST have been compared, but this comparison does not show any significant differences. The main difference found is that EnergyPLAN generally suggests lower HP capacities and identifies lower total system costs than MODEST.

Sensitivity analyses show that the results are sensitive to electricity and fuel price levels; thus, if the electricity prices increase relative to the fuel price levels, the potential for HPs will decrease and vice versa. The sensitivity to changes in HP investment costs and COP are significantly lower than for the energy prices, and changes in these parameters are not seen as a risk to the feasibility of HPs.

Acknowledgement

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Appendix. Simulation output data

Table 5
Operational data from the key calculations from EnergyPLAN (EP) and MODEST (MO) for the scenarios 2013 and 2025 in the base line and closed system calculations. Identified optimal capacities of electric boilers and heat pumps under "Capacities."

		2013								2025							
		Reference		Potential		Reference closed		Potential closed		Reference		Potential		Reference closed		Potential closed	
		EP	MO	EP	MO	EP	MO	EP	MO	EP	MO	EP	MO	EP	MO	EP	MO
Fuel (TWh)	Coal	35.8	44.6	37.1	44.6	38.3	52.8	42.8	54.5	10.2	10.2	5.4	3.8	9.1	7.9	10.3	10.3
	Oil	0.7	0.9	0.7	0.9	1.8	1.0	1.5	1.0	1.3	0.6	0.9	0.2	3.7	3.7	2.4	0.6
	Gas	9.9	10.9	5.2	6.0	11.2	11.8	6.1	7.1	9.4	9.7	3.4	2.4	10.7	12.9	5.8	5.3
	Biomass	17.6	20.6	15.6	18.3	19.0	23.5	17.8	21.7	31.9	35.4	15.6	14.0	29.7	30.1	30.8	33.6
	TOTAL	63.9	77.0	58.6	69.8	70.3	89.0	68.1	84.3	52.7	55.9	25.2	20.4	53.1	54.6	49.3	49.8
Costs (M€)	Fuel	1213	1369	1024	1207	1370	1572	1209	1452	1433	1533	674	552	1503	1670	1328	1331
	Variable operation	48	62	50	63	54	75	60	78	39	41	22	21	37	36	43	47
	Fixed operation	610	610	630	610	610	610	633	610	897	896	934	896	897	896	917	896
	Investments	1145	1143	1201	1143	1145	1143	1212	1143	1671	1669	1778	1669	1671	1669	1730	1669
	Additional investments	–	2	–	87	–	2	–	87	–	2	–	192	–	2	–	114
	Electricity exchange	45	−186	102	−93	0	−367	0	−312	−159	−134	369	562	0	0	0	0
	TOTAL	3061	3076	3007	3032	3179	3110	3114	3073	3881	4005	3777	3889	4108	4271	4018	4057
Electricity production (TWh)	Wind onshore	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
	Wind offshore	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2
	Solar PV	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	Waste electricity	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
	CHP	13.2	13.3	13.2	13.2	11.5	13.3	12.1	13.2	13.9	13.7	7.2	4.5	9.7	9.3	9.6	10.9
	Condensing power plant	4.1	9.2	4.9	9.3	7.7	14.1	9.6	15.1	0.2	1.0	0.2	1.0	3.2	3.2	5.6	4.7
	Import	5.3	4.7	6.1	5.8	0.0	0.0	0.0	0.0	3.9	3.7	10.2	13.2	0.0	0.0	0.0	0.0

	Export/waste	3.6	8.3	2.8	6.9	0.2	8.3	0.2	6.9	7.6	8.0	2.0	1.8	2.0	2.1	1.2	0.7
	Demand	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9
Heat production (TWh)																	
Group 1	Boiler	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Waste heat	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Solar thermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Cooling	–	0.0	–	0.0	–	0.0	–	0.0	–	0.0	–	0.0	–	0.0	–	0.0
	Heat demand	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Group 2	Boiler	8.4	8.3	1.2	1.6	8.5	8.3	1.0	1.6	6.2	6.7	0.6	1.0	6.2	6.0	0.5	0.4
	CHP	0.1	0.2	0.1	0.0	0.0	0.2	0.0	0.0	1.4	1.1	1.1	0.2	1.0	1.8	1.0	0.9
	Waste heat	2.0	1.9	2.0	1.9	2.0	1.9	2.0	1.9	2.0	1.9	2.0	1.9	2.0	1.9	2.0	1.9
	Electric boiler	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.1	0.2
	Heat pump	0.0	0.0	7.2	6.9	0.0	0.0	7.5	6.9	0.0	0.0	5.9	6.6	0.0	0.0	6.1	6.3
	Solar thermal	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Cooling	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2
	Heat demand	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Group 3	Boiler	0.0	0.0	0.0	0.0	2.4	0.0	1.5	0.0	0.3	0.0	0.0	0.0	5.7	7.1	2.6	0.1
	CHP	19.0	19.0	19.0	19.0	16.6	19.0	17.5	19.0	18.2	18.6	8.9	6.2	12.8	11.5	12.5	14.8
	Waste heat	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
	Electric boiler	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.6	1.5
	Heat pump	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.6	12.3	0.0	0.0	2.8	2.3
	Solar thermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Cooling	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3
	Heat demand	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4
Capacities (MW)	Electric boiler 2	325	325	325	325	325	325	325	325	325	325	325	325	325	325	325	519
	Heat pump 2	0	0	1170	1317	0	0	1275	1317	0	0	1170	1438	0	0	1200	1350
	Electric boiler 3	0	0	0	0	0	0	0	0	0	0	0	171	0	0	1100	1716
	Heat pump 3	0	0	0	0	0	0	0	0	0	0	1950	2631	0	0	360	817

Table 6
Operational data from the key calculations from EnergyPLAN (EP) and MODEST (MO) for the scenario 2025 in the sensitivity analysis calculations. Identified optimal capacities of electric boilers and heat pumps under "Capacities."

		Sensitivity analyses: 2025															
		Electricity price: High		Electricity pric: Low		Fuel price: High		Fuel price: Low		Investment costs: High		Investment costs: Low		COP: High		COP: Low	
		EP	MO	EP	MO	EP	MO	EP	MO	EP	MO	EP	MO	EP	MO	EP	MO
Fuel (TWh)	Coal	11.6	14.2	2.5	1.1	2.6	1.1	12.5	16.2	6.4	5.3	4.8	2.6	4.3	3.2	8.6	5.8
	Oil	1.2	0.8	0.8	0.1	0.8	0.1	1.3	0.9	1.0	0.3	0.9	0.1	0.8	0.2	1.1	0.3
	Gas	10.1	13.5	0.7	0.7	0.7	0.6	13.8	17.1	4.2	3.3	3.5	1.1	3.1	1.7	5.5	3.2
	Biomass	35.3	47.1	6.4	5.8	6.7	5.7	38.9	53.6	18.7	18.9	13.7	10.2	12.3	12.1	25.7	20.0
	TOTAL	58.2	75.6	10.3	7.6	10.8	7.5	66.4	87.8	30.2	27.9	22.8	14.1	20.6	17.2	40.8	29.3
Costs (M€)	Fuel	1573	2068	272	208	367	274	1216	1612	809	752	615	378	554	463	1090	787
	Variable operation	50	66	9	12	10	12	57	78	26	26	20	17	18	19	33	28
	Fixed operation	902	896	950	896	953	896	897	896	935	896	926	896	934	896	916	896
	Investments	1686	1669	1826	1669	1832	1669	1671	1669	1781	1669	1755	1669	1777	1669	1725	1669
	Additional investments	–	21	–	259	–	280	–	2	–	181	–	179	–	213	–	147
	Electricity exchange	−426	−844	485	586	698	865	−484	−876	268	418	413	679	431	589	80	412
	TOTAL	3785	3874	3542	3631	3860	3993	3357	3379	3819	3940	3729	3816	3714	3847	3844	3936
Electricity production (TWh)	Wind onshore	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
	Wind offshore	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2
	Solar PV	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	Waste electricity	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
	CHP	16.0	16.7	2.6	1.6	2.8	1.5	17.5	18.0	8.7	6.7	6.5	2.8	5.7	3.7	11.6	7.2
	Condensing power plant	2.1	7.5	0.0	0.0	0.1	0.0	3.3	10.7	0.2	1.0	0.2	1.0	0.3	1.0	0.3	1.0
	Import	2.3	1.7	16.4	18.5	16.1	18.1	1.2	1.2	8.7	10.1	11.0	15.5	11.3	13.6	6.2	10.2
	Export/waste	9.1	14.8	1.3	0.9	1.3	0.9	11.6	19.3	2.8	1.6	1.8	1.5	1.8	1.9	4.5	1.5
	Demand	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9
Heat production (TWh)																	
Group 1	Boiler	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Waste heat	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Solar thermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Cooling	–	0.0	–	0.0	–	0.0	–	0.0	–	0.0	–	0.0	–	0.0	–	0.0
	Heat demand	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Group 2	Boiler	1.5	1.1	0.4	0.1	0.2	0.0	2.5	1.4	0.8	1.5	0.4	0.0	0.5	0.4	2.0	1.2
	CHP	3.5	5.1	0.1	0.0	0.2	0.0	5.1	6.8	1.3	0.3	1.4	0.0	1.2	0.1	1.2	0.2
	Waste heat	2.0	1.9	2.0	1.9	2.0	1.9	2.0	1.9	2.0	1.9	2.0	1.9	2.0	1.9	2.0	1.9
	Electric boiler	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Heat pump	2.6	2.0	7.1	7.3	7.2	7.8	0.0	0.0	5.5	6.1	5.9	7.8	6.0	7.3	4.5	6.4
	Solar thermal	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Cooling	0.0	0.4	0.0	0.2	0.0	0.2	0.0	0.4	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2
	Heat demand	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Group 3	Boiler	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
	CHP	18.5	18.6	3.6	2.2	3.7	2.2	18.5	18.6	10.8	9.3	7.6	4.0	6.7	5.2	15.1	10.1
	Waste heat	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
	Electric boiler	0.0	0.0	0.0	0.7	0.0	0.3	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.8
	Heat pump	0.0	0.0	14.9	15.7	14.7	16.1	0.0	0.0	7.7	8.4	10.9	14.6	11.9	13.5	3.3	7.7
	Solar thermal	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Cooling	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3	0.0	0.3
	Heat demand	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4
Capacities (MW)	Electric boiler 2	325	325	325	456	325	325	325	325	325	325	325	325	325	325	325	325
	Heat pump 2	450	403	1425	1748	1530	2014	0	0	1050	1242	1275	2025	1138	1748	750	1356
	Electric boiler 3	0	0	0	897	0	669	0	0	0	1261	0	0	0	0	0	1175
	Heat pump 3	0	0	3000	3671	3150	3899	0	0	1350	1541	2400	3671	2450	2802	562	1627

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PAPER 2

Large combined heat and power plants in sustainable energy systems

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Large combined heat and power plants in sustainable energy systems

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HIGHLIGHTS

- The feasibility of CHP plant types is analysed in a 100% renewable energy context.
- Three large-scale CHP types are compared in full system application.
- Four scenarios are constructed and compared in terms of system costs and fuel consumption.
- Combined cycle gas turbines plants show to be the most feasible technology.

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ABSTRACT

In many countries, the electricity supply and power plant operation are challenged by increasing amounts of fluctuating renewable energy sources. A smart energy system should be developed to integrate as much energy supply from fluctuating renewable sources and to utilise the scarce biomass resources as efficiently as possible. Using the advanced energy systems analysis tool EnergyPLAN and Denmark as a case, this analysis defines which of the three assessed types of CHP plants connected to district heating systems is most feasible in terms of total socioeconomic costs and biomass consumption. It is concluded that the CCGT CHP plant is the most feasible both from a technical analysis and a market economic analysis with electricity exchange. It is found that the current economic framework for large CHP plants in Denmark generates a mismatch between socio economy and business economy as well as an unsustainable level of biomass consumption. Therefore, the regulatory framework should generally be considered in long-term planning of sustainable CHP systems.

1. Introduction

In many countries, governments are developing strategies for renewable energy (RE), and increasing amounts of renewable energy are introduced to reduce energy costs, GHG emissions and the dependence on fossil fuels, and also develop green energy industry and jobs, etc. The increasing scale of fluctuations in the energy production from renewable sources is challenging the existing energy systems that have to cope with these fluctuations.

1.1. The case of denmark

Denmark has many years of experience with integrating fluctuating wind power and solar PV, which in the first six months of 2014 covered 43% of the electricity consumption [1]. This is possible mainly due to flexible combined heat and power (CHP) plants and thermal storages connected to extensive district heating (DH) systems. Scenario analyses of Denmark in 2011 have shown that a transition to a 100% renewable energy supply in 2050 can be done in a socioeconomically beneficial way [2,3]. On the basis of this work, the Danish government developed a vision and an official policy aiming at a 100% renewable energy supply in Denmark by 2050 [4].

Denmark is an interesting case of study because of its ambitious RE target together with the fact that the country has no substantial hydropower resources available. This condition makes it more difficult to reach the target with a sustainable level of biomass consumption and the integration of large amounts of fluctuations in the supply. Hydropower can provide a large flexibility and its absence in Denmark creates a demand for other flexibility measures (see Fig. 1).

The Coherent Energy and Environmental System Analysis (CEESA) project suggests combined cycle gas turbine (CCGT) units as a flexible and fuel efficient production capacity for large CHP

Abbreviations: APF, advanced pulverised fuel; CCGT, combined cycle gas turbine; CFB, circulating fluidised bed; CHP, combined heat and power; DH, district heating; RE, renewable energy; IC, interconnection (of electricity grids).

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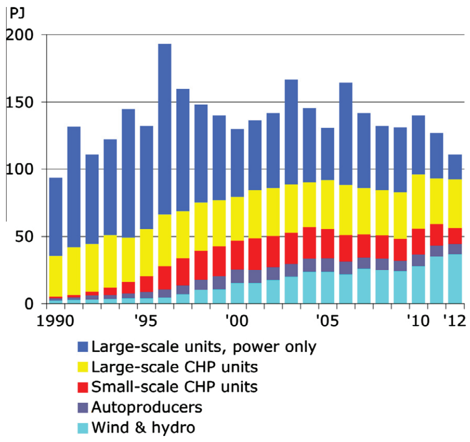

Fig. 1. Electricity production by type of producer [5].

(extraction and condensing) in Denmark in the context of 100% RE, without comparing different technologies though [6]. In reality, this is not what is being implemented nor planned.

Several of the large coal-fired CHP plants in Denmark are challenged by low electricity prices and several plants have already been decommissioned or are planned to be in the near future. Currently, biomass is being promoted to substitute coal for the CHP plants [7]; old coal plants are being converted to biomass [8], and new biomass CHP plants are being planned [9]. Large CHP plants often have a technical lifetime of up to 40 years, which means that a CHP plant built today will be a part of the RE transition and may still be in operation in 2050.

A number of studies have analysed the power plant technologies and their system performances. Srinivas and Reddy have analysed and compared a number of different CCGT technologies [10]. In [11], a circulating fluidised bed (CFB) technology is analysed through simulation and testing to assess its efficiency and economy, and Utt and Giglio compare CFB and advanced pulverised fuel (APF) technologies for large-scale utility application [12]. Pihl et al. and Francois et al. have analysed the use of gasification of biomass for cogeneration for high efficiency and flexibility [13,14], and Hong et al. show for a region in China that the flexibility of power plants is important to the integration of renewable energy [15]. However, the CHP technologies have not previously been analysed and compared in the dynamic context of a 100% renewable energy system.

In this study, three different common large CHP plant types are modelled as an integrated part of a 100% renewable energy system to assess their feasibility in this future context. The analysed CHP plant types are CCGT plants, CFB plants, and APF plants, because these types are commonly suggested in the debate on how to integrate renewable energy [8,9,16].

1.2. A smart energy system approach

With a high share of fluctuating supply and limited biomass sources in the system, it is essential to develop a flexible energy system that can absorb the fluctuations in a resource efficient way. A smart energy system is the collective of electric smart grids, thermal smart grids, and smart gas grids operated intelligently to utilise energy sources efficiently, where the supplies of electricity, heating, cooling, transport, and industry are highly integrated [17]. Fig. 2 illustrates the concept of the change from a system similar to the Danish system of today to a potential future smart energy system with high flexibility and integration of wind power.

In a sustainable energy system, biomass consumption is a critical resource and can affect the global food production if overexploited [18]. Therefore biomass should as far as possible be used where the alternatives to biomass are most expensive, mainly heavy transport, and not for, e.g., heating [19].

In smart energy systems, the CHP plants play a central role due to their ability to regulate for the fluctuating wind power production. CHP plants will be operating less, but they are still important to the regulation for fluctuations in wind power production [17].

In Section 2, the methodology of the study is presented, including a description of the computer model used in the analysis, the scenario structure, and the applied assumptions. In Section 3, the results of the two parts of the analysis are presented and discussed; the technical energy systems analysis and the market economic analysis of the electricity exchange potential. This is followed by a brief conclusion of the study in Section 4.

2. Methodology

In this chapter, the methodology applied in the study is presented. The economic perspective is described followed by a presentation of the applied energy system modelling tool EnergyPLAN, and finally, the analysis structure and scenarios are presented.

2.1. Socioeconomic perspective

Long-term planning of energy supply and infrastructure is of societal interest and therefore socioeconomic costs are calculated in this study. Socioeconomic costs are here understood as the total national costs of the energy system, excluding taxes, levies, subsidies and other measures of regulation or allocation, in opposition to a business economic approach in which these are included.

2.2. The EnergyPLAN model

EnergyPLAN is an advanced modelling tool for analysing technical energy systems. The model has been developed continuously since 1999 in the Sustainable Energy Planning research group at Aalborg University. In this study, the EnergyPLAN version 11.3 is applied. The specific algorithms of the model are not elaborated in this paper, but documented thoroughly in [20].

2.2.1. Overview of the model

The tool is designed for modelling large-scale integration of renewable energy and radical technological changes of energy systems. The tool has been used to model a number of case studies of system flexibility and 100% renewable energy plans for municipalities [21] and countries [3,22,23], as well for the assessment of specific technologies in the context of larger energy systems [24]. It has also been used to model smart energy systems in different contexts [17].

EnergyPLAN is a deterministic input–output modelling tool that allows the user to model an energy system with the supply and demand of electricity, heating, gas and transport in an hourly time resolution of one full year [25]. The model inputs are technology specifications, such as capacities and efficiencies, annual demands, and annual production of fluctuating renewable energy, waste and industrial surplus energy. The annual values are distributed to hourly values by input of hourly distribution patterns. The outputs consist of the hourly system operation with the provision of a number of annual and monthly summaries of, e.g., fuel consumption and system costs.

Fig. 3 shows a flow diagram of the major components included in the calculations performed by the EnergyPLAN model. It can be

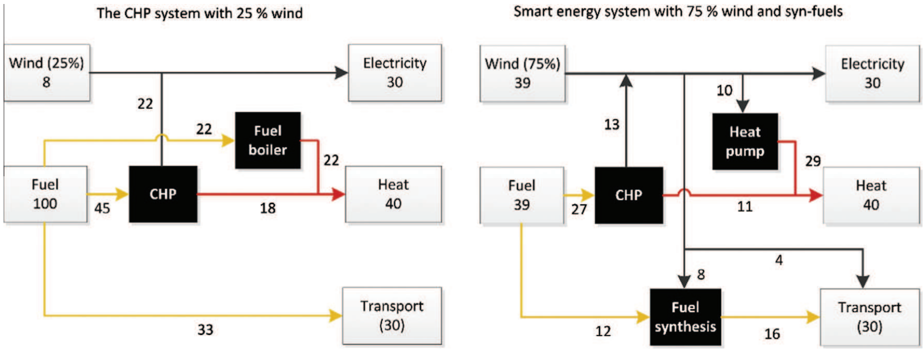

Fig. 2. Illustration of the change to a "Smart Energy System." White boxes indicate supply and demand. Black arrows indicate electricity, red heating and orange fuel flows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

seen that the demands of electricity, heating, transport and industry are covered and that electricity, thermal energy, and fuel in different forms can be converted flexibly in a number of different conversion technologies.

The costs in EnergyPLAN are annual values calculated as a sum of the investment costs, fixed and variable operation and maintenance costs, fuel and fuel handling costs, and electricity exchange costs and income. The investment costs are annualised according to the technical lifetime of the individual technologies and a discount rate. In this study, a discount rate of 3% is applied.

2.2.2. Application of EnergyPLAN

In EnergyPLAN, a regulation strategy is chosen to decide how the model should set the merit order of the different supply technologies, e.g., when to operate CHPs, heat pumps, power plants, etc. Generally, the use-it-or-loose-it energy sources; wind, solar, geothermal, waste heat, industrial surplus, etc., are prioritised in the model. There are fundamentally two regulation strategies; Technical regulation and Market economic regulation, with a number of sub options for each. In this study, both of these have been applied respectively in the two parts of the analysis, which is elaborated in the following two sections.

The technical regulation strategy is applied in the technical analysis of the different CHP plant types. The technical regulation strategy, with sub option "balancing both heat and electricity demands" applied, seeks to minimise the fuel consumption by utilising the resource supply as efficiently as possible including minimisation of excess electricity production. This means for example that the CHP production, for DH using thermal storage, is prioritised over power-only production, but in situations with excess

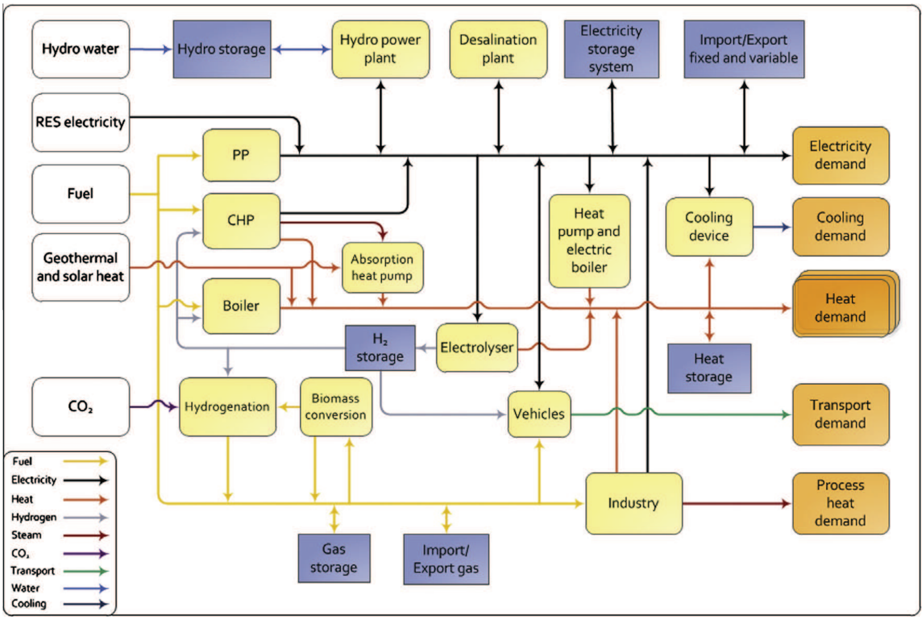

Fig. 3. Flow chart illustrating energy sources (white), conversion technologies (yellow), storage and exchange options (blue) and demands (orange) in EnergyPLAN [20]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

heat production, the CHP may be replaced with condensing power production. This is modelled in "island mode", which means that there is no electricity exchange with other countries and no income is calculated from potential excess electricity. This is done to assess how efficiently the system can operate from a technical perspective before including electricity exchange in the second part of the analysis.

The market economic regulation is used in the analysis to assess the potential for electricity exchange of the different scenarios. The market economic regulation strategy seeks to meet the different demands at the lowest marginal costs from the plant's perspective, hence including taxes on the energy production when choosing the cheapest option amongst, e.g., CHP, heat pumps, fuel boilers, and condensing power production. In this case, the CHP will operate to cover the demand no matter the system efficiency, if this is the least cost solution. This method is applied to assess the potential benefit of electricity trade with the neighbouring countries for the scenarios with the different CHP plants.

2.3. Scenario definition

The scenarios are based on a scenario developed for the CEESA project, which is defined as a 100% renewable energy system for Denmark in year 2050 and resembles a smart energy system [6]. The CEESA system is here modified with the characteristics of the three types of power plants in four alternative scenarios (see Table 1). The CEESA scenario is designed with the characteristics of Denmark, but the technological solutions suggested here could apply to any country or region with high wind and solar PV power penetration and low amounts of hydropower.

The four scenarios are compared in terms of two indicators:

(1) Systems costs.
(2) Fuel consumption (here biomass).

To analyse the three different types of CHP plants and their efficiencies in a renewable energy system, four scenarios have been constructed and analysed in EnergyPLAN. The scenarios comprise a full model of the energy system in Denmark. The differences between the scenarios are only the adjustments related to the CHP plant type. The scenarios are presented in Table 1.

The CFB technology has a low electric efficiency compared to the thermal efficiency (see Table 2) which means that the heat demand is easily covered in the areas where these plants are installed and a capacity of 2500 MW-e will not be efficiently utilised. Therefore two scenarios with lower electric capacities are analysed for the CFB technology as seen in Table 1.

In all four scenarios, there is a condensing power plant capacity of CCGT plants making a total dispatchable electric capacity of 10,300 MW. The CFB plants are assumed not to be able to operate in condensing mode, so here the CHP capacity is additional to this condensing power capacity.

In the systems analysed in this study, there are no fossil fuels, hence all fuels consumed are bioenergy sources. The CCGT plants consume gas as fuel and this gas is produced from the gasification of a biomass source, here assumed to be wood chips.

Table 1
Definition of capacities of thermal and electric production of the CHP plants in the four scenarios. The CCGT scenario capacities are defined in the CEESA scenario.

	CCGT	CFB Low	CFB High	APF
CHP electric capacity (MW-e)	2500	850	2000	2500
CHP thermal capacity (MW-th)	1290	1290	3050	2690

2.4. Technology assumptions

The general technology assumptions for costs, efficiencies, etc., used in the study are found in [26] where nothing else is mentioned. The assumptions for the CEESA scenario can be found in [6]. The main technology assumptions are listed in Table 2.

The CCGT plant is assumed to use gas from gasified wood chips. It is modelled to be able to start, stop and regulate its production as needed to balance supply and demand from hour to hour.

The CFB plant is assumed to be operating base load in the heating season, where it is found to be most feasible, and not operating in the summer season, in total about 5100 operating hours per year. As a flexibility measure, the CFB plants are assumed to be able to by-pass the turbine resulting in reduced electricity production. The by-passed steam can then be used for DH production.

The APF plant is modelled similar to the CCGT plant, but because of its limited ability to start and stop the boilers needed to run the turbine, an aggregated minimum load of 5% is included in the scenario equivalent to 125 MW-e.

2.5. Market economic assumptions

In the market economic electricity exchange analysis, the scenarios are analysed with regard to different interconnection (IC) capacities to neighbouring countries. 0 MW represents a system with no connection to other countries and 5400 MW is the average traded capacity available today for Denmark. Then a lower capacity (2000 MW) and a higher capacity (8000 MW) are included to show how different capacities influence the economy of the systems. The costs related to the infrastructure in the IC cables are not included in the analysis, but this does not influence the conclusions of this study.

Different levels of electricity prices on the external electricity markets are included in the analysis to show how the system economy may vary from one year to another:

- An average price level of 72.6 €/MW h.
- A low electricity price level representing a "wet year" with a high amount of hydropower production in Norway and Sweden, with an average price of 48.2 €/MW h
- A high electricity price level representing a "dry year" with a low amount of hydropower production in Norway and Sweden, with an average price of 130.5 €/MW h.

The costs are calculated based on the electricity price projection from The Danish Energy Agency [28] inspired by the methodology applied in [29].

Table 2
Plant characteristics of the three analysed CHP plant types. They represent expected values for 2040–50 with improved technology performance. Costs are given in million Euro per megawatt (M€/MW).

	CCGT	CFB	APF
Fuel	Gas	Wood chips	Wood pellets
Electric efficiency, condensing (%)	62	–	54
Electric efficiency, CHP (%)	59	40[a]	45
Thermal efficiency, CHP (%)	33	61[b]	49
Minimum load (%)	0	100	10
Investment costs (M€/MW-e)	0.79	0.93[c]	1.89
Fixed O&M costs (M€/MW-e/year)	0.03	0.05[c]	0.06
Investment life time (years)	25	25[c]	40

[a] The electric efficiency data is obtained from [11].
[b] This is assuming that the production efficiencies are equivalent to an efficient waste-to-energy plant with flue gas condensation.
[c] The cost data are obtained from [27].

Hourly distributions of electricity prices from Nordpool-Spot, wind power production in Denmark and electricity demand in Denmark from 2012 have been applied in all the analyses.

The costs of wood chips are assumed to be 5.66 €/GJ and the costs of wood pellets are assumed to be 8.50 €/GJ. The gas is produced from the gasification of wood chips which makes an indirect cost of 7.87 €/GJ when conversion losses are included.

In the electricity exchange analysis, an economic constraint on the consumption of biomass at DH boilers is added. This is done to limit the biomass consumption to the level identified in the CEESA project [6] as being sustainable in the Danish context. The point of reference here is the CCGT scenario with 0 MW IC capacity and an average electricity price level. The constraint on the consumption of biomass for heat-only production reduces the feasibility of this production and thereby reduces the consumption. The value applied is 7.76 €/GJ of biomass consumed in DH boilers. The consequences of the economic constraint for total scenario costs and biomass consumption are elaborated on in the results section.

3. Results and discussion

In this section, the results of the analyses are presented and discussed.

3.1. Technical analysis results

To illustrate the changes in the system as a result of the different CHP plant types, the total heat production in the system is presented in Fig. 4 for the four scenarios. Here it can be seen that the CCGT scenario has the lowest CHP production. The production is higher in the other scenarios because these CHP technologies are less flexible and have lower electric efficiencies compared to heat and thereby produce more heat for the same electricity production. This reduces the potential for utilising heat pumps and waste heat, as can be seen in the figure.

The main results of the technical scenario analysis are illustrated in Fig. 5. These are the results for the whole energy system of the scenarios and not only what is directly related to the CHP plants, but also including industry, transport, etc. It can be seen that the CCGT scenario has the lowest costs and the lowest biomass consumption, as also indicated by Fig. 4. The CFB Low scenario has very similar results, but the costs are 81 M €/year higher than in the CCGT scenario and 0.8 TW h more biomass is consumed per year. If the high CFB capacity is assumed, the biomass use increases by 13.3 TW h/year and cost increases by 160 M€/year compared to the CCGT scenario. In the case of the APF boiler type CHP, the system would use 0.4 TW h more biomass and cost 680 M€/year more than the CCGT.

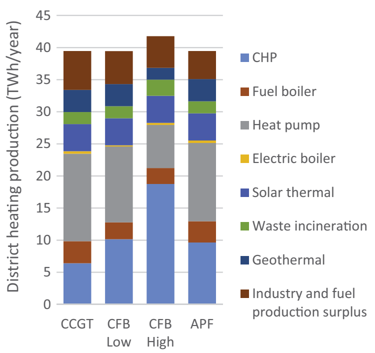

Fig. 4. Sources of the DH production in the four scenarios.

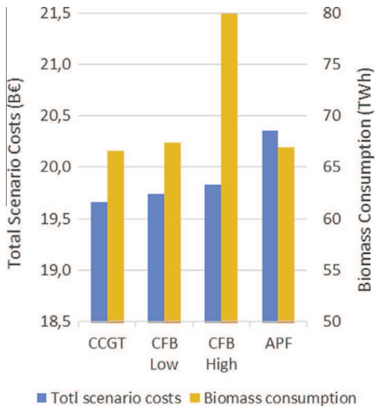

Fig. 5. Main results for the scenarios of the technical energy systems analysis showing values for the whole energy system.

As a sensitivity analysis of the results, three key parameters have been changed for the four scenarios. These are investment costs of the CHP units, efficiencies (both heat and electricity) of CHP units, and biomass price. The analysis shows that under similar conditions CCGT remains the most cost efficient plant type. The results for the CCGT and the CFB Low scenarios are shown in Fig. 6.

In Fig. 6 it can be seen that, for example in the case of an increase of 10% in investment costs of the CCGT plant, the scenarios will have the same cost. It can also be seen that a reduced efficiency of 10% of the CHP units in the CCGT scenario will make this scenario more costly than the CFB Low scenario. Generally, it can be seen that even a small change in biomass price can have a relatively large impact on the overall system costs.

3.2. Market economic analysis results

In Figs. 7 and 8, the development of the scenario costs with increasing IC capacities can be seen. This is not a study of the IC capacity level and the infrastructure investment costs of these are therefore not included. This makes it possible to see only the

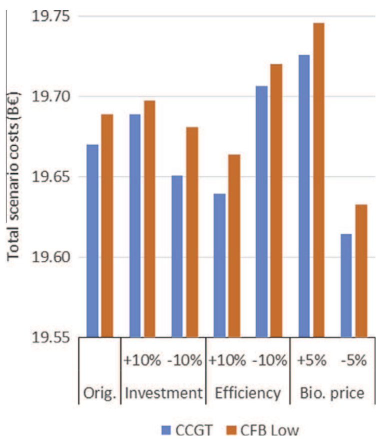

Fig. 6. Results of sensitivity analysis for the scenarios CCGT and CFB Low of sensitivity to investment costs and efficiencies of CHP units and biomass price.

change in costs as a result of the changed CHP technology. In Figs. 7 and 8, it is important to notice the changes between the scenarios rather than between IC capacities.

The overall least cost option of the analysed systems is the CCGT scenario. Fig. 7 illustrates an analysis of the scenarios with the biomass constraint and, in Fig. 8, the same analysis is shown, but without the biomass constraint. It can be seen that the CCGT scenario has lower costs with the biomass constraint, but in the situation in which this is removed, the CFB Low scenario is the least cost solution. However, it should be noted that the overall least cost option is the CCGT in the configuration with the biomass constraint.

Table 3 shows the results of the analyses of the scenarios with different electricity price levels. It can be seen that both in the cases of higher electricity prices and of lower electricity prices, the CCGT scenario is the least cost option.

3.3. Fuel consumption in a market economic context

The biomass consumption is closely related to the amount of electricity that is being exported from the system. For example, if the external prices are high it may be feasible to produce more electricity from the CHP or Condensing power plants in the system to export it and thereby consume more biomass inside the system borders. In this case, another fuel or energy source at a power plant in the importing country is replaced and thereby the fuel or energy consumption at this place will be reduced. Opposite if the external electricity prices are low.

It is therefore important to notice the biomass consumption at 0 MW IC capacity, because this indicates the fuel efficiency of the particular scenario configuration. At 0 MW IC capacity, only the demand inside the system is covered and no demands elsewhere. This is used as a point of reference because all scenarios will behave differently in relation to the external electricity market, while the systems with 0 MW IC capacities can be compared.

As explained in the above sections, the biomass constraint applied has an impact on the systems and limits the biomass consumption. In Fig. 9, the scenarios are presented for the different IC capacities with the biomass constraint, and in Fig. 10, the same analysis is illustrated without the constraint. Here it can be seen that the biomass consumption is significantly higher in the configurations without the biomass constraint. This is mainly due to the increased operation of the biomass boilers without the constraint and the lower feasibility of using CHP.

It can be seen that the biomass consumption for the CCGT is lower in most of the scenario configurations with biomass boiler constraint, including the configurations with 0 MW, indicating that the CCGT scenario operates most fuel efficiently.

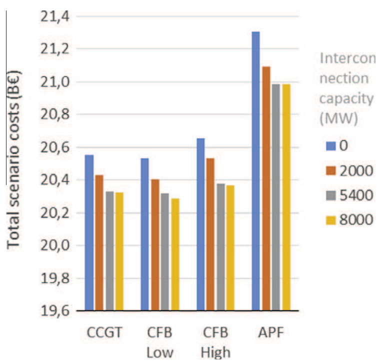

Fig. 7. Total scenario costs for the scenarios of varying IC capacities.

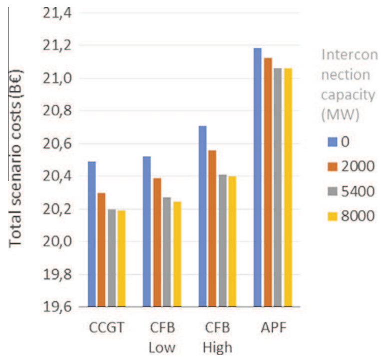

Fig. 8. Total costs for the scenarios of varying IC capacities without economic constraint on biomass consumption for fuel boilers in DH.

Table 3
Comparison of scenario costs of the scenarios for different external electricity price levels at 5400 MW IC capacity.

Scenario (B€/year)	CCGT	CFB Low	CFB High	APF
High	20.24	20.31	20.44	21.49
Average	20.19	20.27	20.40	21.06
Low	20.15	20.23	20.32	20.76

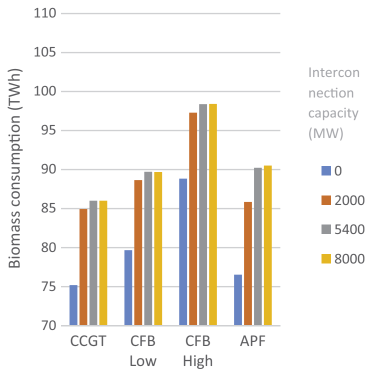

Fig. 9. Total biomass consumption for the scenarios with varying IC capacities.

3.4. Future planning for CHP plants

This study shows that a CCGT plant under the given conditions is the most feasible type of CHP plant for smart energy systems. As mentioned in Section 1.2, a smart energy system is a very resource efficient way of developing renewable energy systems, but it requires a number of changes apart from the CHP plants. It is important that the whole energy system is developed with the purpose of integrating high amounts of fluctuating renewables and here the CCGT CHP plants have been identified as a potential for creating synergy between electricity, heating and gas systems. This means that the planning of flexible CHP plants should be started as soon as possible to support the continuous integration of renewable energy sources.

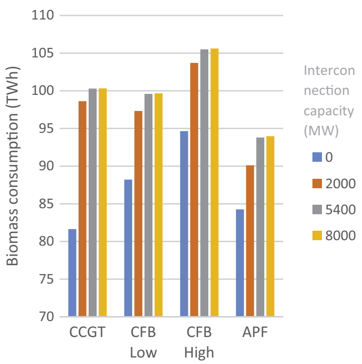

Fig. 10. Total biomass consumption with varying IC capacities without economic constraint on biomass consumption for fuel boilers in DH.

The consumption of biomass is a critical issue especially in relation to the CFB plants, because the costs are similar to those of the CCGT plants; but at larger capacities, the biomass consumption increases dramatically, as seen in the results. The economy of large CHP plants is very dependent on the regulatory framework. As the costs of the two types of systems are similar, the economic regulation will be a highly determining factor in the concrete choice between these two types.

On this basis, it is recommended to make a long-term revision of the regulatory economic framework for DH production, e.g., by introducing a tax on biomass for DH boilers to make sure that these support a sustainable development towards a renewable energy system. It is specifically suggested to consider an economic constraint on biomass consumption for fuel boilers used for DH supply.

4. Conclusion

It can be concluded that, of the analysed CHP plant types, the CCGT plant will have the lowest overall system costs and biomass consumption in a smart energy system context, and the CCGT plant is therefore the preferred type of CHP plant for large-scale implementation.

Compared to the other types, the CCGT CHP plants are more efficient and adapt better to operation under different conditions. Furthermore, they have the lowest biomass consumption in all analysed contexts and the lowest costs, except when the biomass constraint is removed.

It can also be concluded that using marginal price signals alone without any consideration of limiting the use of biomass does not enable least cost solutions and increases the biomass consumption. It can therefore be recommended to consider a revision of the regulatory framework to limit the consumption of biomass.

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PAPER 3

Mapping of potential heat sources for heat pumps for district heating in Denmark

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Mapping of potential heat sources for heat pumps for district heating in Denmark

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ABSTRACT

The ambitious policy in Denmark on having a 100% renewable energy supply in 2050 requires radical changes to the energy systems to avoid an extensive and unsustainable use of biomass resources. Currently, wind power is being expanded and the increasing supply of electricity is slowly pushing the CHP (combined heat and power) plants out of operation, reducing the energy efficiency of the DH (district heating) supply. Here, large heat pumps for district heating is a frequently mentioned solution as a flexible demand for electricity and an energy efficient heat producer. The idea is to make heat pump use a low temperature waste or ambient heat source, but it has so far been very unclear which heat sources are actually available for this purpose.

In this study eight categories of heat sources are analysed for the case of Denmark and included in a detailed spatial analysis where the identified heat sources are put in relation to the district heating areas and the corresponding demands. The analysis shows that potential heat sources are present near almost all district heating areas and that sea water most likely will have to play a substantial role as a heat source in future energy systems in Denmark.

1. Introduction

Large-scale introduction of RE (renewable energy) sources for electricity production, such as wind or solar power, increases fluctuation in the supply and reduces the general price level of electricity because of the low marginal production costs of these producers [1]. In Denmark, the development of the electricity prices means that CHP (combined heat and power) plants has fewer operating hours than earlier. In Fig. 1 it can be seen how wind power is increasing and the production from small-scale CHP is decreasing to about one third in ten years. The production on large-scale CHP units is relatively constant even though its production capacity is decreasing in the same period [2].

The decreasing electricity production from CHP units also gives a lower heat production for the district heating (DH) supply and this deficit in heat production needs to be produced from other sources [3]. In the short term, fuel boiler units increase their production, which is an inefficient use of energy resources. In the longer term, other sources, such as solar thermal, geothermal and heat pumps, are predicted to play a larger role in the DH supply, and these have been increasing over the last years [4].

1.1. Heat pumps as a solution

Large-scale compression heat pumps in particular have several benefits for DH production in the future; they can consume electricity when the wind and solar production is high and they produce heat, which can replace the production by fuel boilers. Heat pumps as integrated production units in DH systems can provide a stable and efficient heat supply [5], but it is dependent on a heat source. Compression heat pumps contain a refrigeration cycle that enables cooling of a low-temperature heat source to deliver heating at a higher temperature level using electricity in a compressor to drive the system. The temperature, flow, volume and other parameters of the heat source will determine the possible efficiency. The required supply temperature from the heat pump will depend on the temperature level of the DH network to where the heat pump will be supplying. The higher supply temperature needed from the heat pump, the lower efficiency. Therefore, reducing the

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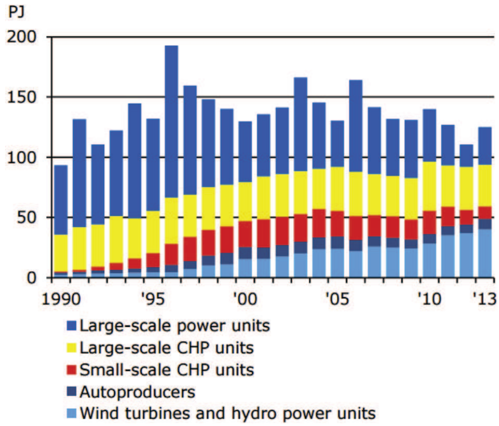

Fig. 1. Electricity production by type of producer. From the Danish annual energy statistics 2013 [2].

temperature levels of DH networks will increase the efficiency of using low-temperature heat sources via heat pumps. 4th generation district heating (4DH) is a concept that highlights the need to reduce the temperature levels of DH networks to adapt them to future energy systems with high shares of RE where large-scale heat pumps play an important role [6].

1.2. Heat pumps in national scenario analyses

Heat pumps are often included as part of future energy scenario analyses for Denmark, because of their ability in integrate wind power, for example in Ref. [7] where a 100% renewable energy scenario for Denmark is presented or in Ref. [8] where three different scenario for the future energy supply in Denmark is compared. In recent scenario analysis from the DEA (Danish Energy Agency) [9] heat pumps also play a central role. These scenarios suggest different levels of heat pump integration, but in general higher shares of wind power correlates with higher integration of heat pumps. None of these studies have considered which heat sources to use or if there are heat sources available to cover the assumed capacities and production or where these are located compared to the heating demands.

1.3. Studies of heat sources for heat pumps

A literature review shows that a large number of studies analyse the use of heat pumps in concrete cases to utilise waste heat or low-temperature heat sources in connection with DH supply.

In Ref. [10] it is suggested to use a combination of different waste heat sources (sewage water, surface water, ground water and others) for DH supply using distributed heat pumps, and concludes that this will increase the system efficiency significantly. A study on utilisation of low-temperature industrial excess heat [11], compares application of different types of heat pumps for the purpose and concludes that the different types of heat pumps are feasible for different applications. In Ref. [12] it is suggested to utilise the already existing waterborne urban infrastructure, such as sewage and drinking water, to recycle heat in the urban areas. A study has evaluated the operation of an existing DH system in Beijing, where a combination of ground water and sewage water as heat sources for heat pumps are applied, and suggested improvements of the system [13].

A case study has analysed the use of lake water in an open-loop as a heating and cooling source, analysing the coefficient of performance (COP) and the environmental impact on the lake ecosystem, showing that it is generally a feasible application [14]. In a similar study, seawater is analysed as a potential heating and cooling source assessing the environmental and economic impacts of the application, concluding that the application is a feasible alternative [15].

A number of studies have documented other potential heat sources, which may not currently be relevant in the Danish context, but will be in many other countries. Some examples of this are [16]: documents a large excess heat production from hydro power plants. In Ref. [17] it is described how thermal springs can be used as heat sources for heat pumps to provide comfort heating. And in Ref. [18] the potential in utilising the water in closed flooded coal mines are analysed and shown to be profitable and reducing CO_2-emissions.

These studies discussed here show examples of how different heat sources can be used for DH supply in specific cases where the particular heat sources have been identified, but no general resources mapping has been found for any of the heat sources, neither for Denmark nor from any other country. A few studies made by Danish consultancies have analysed the energy potential for certain heat sources relevant for heat pumps in Denmark. One is carried out by PlanEnergi with a focus on large scale thermal storage and heat pump technology for district heating [19]. Another one done by Viegand & Maagøe with a focus on how excess heat in the industry can be utilised more efficiently internally or through DH [20]. None of these cover geographical correlation between heat source and heat demand nor do they make a full resource assessment, but rather an assessment of what is feasible from a business economic point of view on the short term. A thorough mapping and assessment of the heat from large-scale facilities has been made in connection with the Heat Roadmap Europe study [21], but this does not cover other low-temperature or ambient heat sources.

To provide the missing link between the national scenario analysis scale and political ambitions related to heat pumps and the possibilities with different heat sources, this study analyses the geographical relation between the potential heat sources and the demands in the DH networks. This will provide the basis for more qualified system analysis and potential integration of heat pumps in Denmark. The mapping is specific for Denmark, but the methods for the mapping can be used for any country or region. The method can also be used for assessment for sources for district cooling, but in this case it will be necessary to consider other sources than included in this study.

2. Materials and methods

This study is an analysis of the availability of heat sources for heat pumps for application in the DH supply. It includes location of the heat sources relative to the DH networks and rough estimates of the potential energy production from the heat sources. Economic considerations on feasibility of the potential heat pump systems or specific technical or environmental limitations are not included here. A concrete project will always have to rely on a specific assessment of the local conditions.

This section presents the methods, which consists of two main parts; mapping and data collection.

2.1. Mapping methods

The idea of mapping is to find heat sources that are located near DH demand. Heat sources that are far from DH demand may in some cases be relevant to include, but in this study only the heat sources within a radius of 500 m from an existing DH network are counted as potential heat sources. In Fig. 2, the principle is illustrated for an area around two DH networks. The mapped heat sources include point sources such as supermarkets, line sources, here only rivers, and polygon heat sources such as lakes. It can be seen that DH Network 1 has a number of point sources and line sources within the radius of 500 m from the DH network. DH Network 2 has only point sources and none of the DH networks intersect with the polygon heat source, which is therefore not seen as a potential heat source in this study.

The results are shown in a map where the potential heat source volumes are summarised for each municipality. In the Greater Copenhagen area, the municipalities have highly integrated DH systems and therefore the following municipalities, according to [22], are merged to one geographical unit: Copenhagen, Frederiksberg, Tårnby, Gentofte, Gladsaxe, Herlev, Ballerup, Rødovre, Glostrup, Albertslund, Hvidovre, Brøndby, Vallensbæk, Høje Tåstrup, Ishøj, Greve, Solrød, Roskilde and Køge [23].

For the mapping, the software tool ArcMap 10.3 is used.

2.1.1. Heat atlas for Denmark

For the DH networks and the corresponding DH demands, a heat atlas for Denmark is used. This geographic information systems (GIS) data set includes the geographical shapes of all the DH networks in Denmark. The DH networks are administrative spatial units defined by the municipalities in accordance with the Danish heat supply act. The DH demands are calculated on the basis of data from the Danish Building Register. The version of the heat atlas utilised in this analysis has in total 403 unique DH networks registered with a total DH demand of 32.1 TWh/a and a total area of 285.4 km^2. The DH demand is here measured as the final demand, so network losses are not included. The detailed methodology of the heat atlas is documented in Ref. [24].

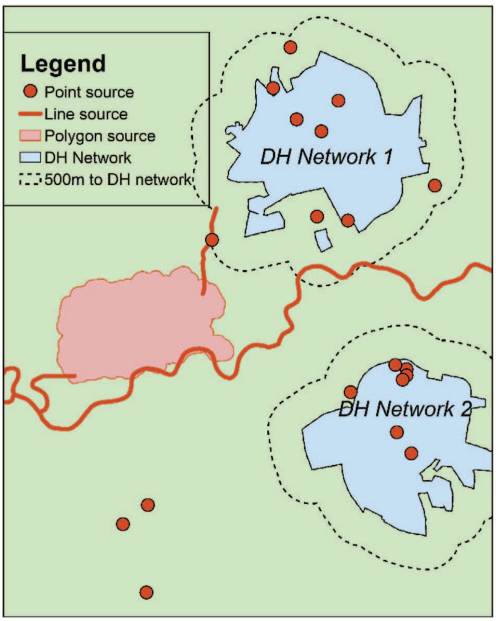

Fig. 2. Illustration of the mapping method. All heat sources that are within or intersect the dotted 500 m distance line are counted as potential heat sources.

2.1.2. Limitations

In this study the purpose is to find low-temperature or waste heat sources for heat pumps. Basically, all options concerning heat pump integration with other facilities having energy production as their purpose are excluded which can be listed as the following:

- CHP plants and waste incineration
- Condensing power plants
- Fuel boilers
- Solar thermal
- Geothermal

The application of heat pumps as an integrated part of another energy facility is here seen as an efficiency measure of the energy plant rather than utilisation of waste heat sources, and this could be relevant without the heat pump. The heat sources included in this study would not be relevant for DH supply without a heat pump.

2.2. Heat sources

In this section, each of the heat sources are described and the methods are presented of how they are analysed. The included heat sources are:

1. Low-temperature industrial excess heat
2. Supermarkets
3. Waste water
4. Drinking and usage water
5. Ground water
6. Rivers
7. Lakes
8. Sea water

Geographical and quantitative data has been collected for all of these from different sources. This is documented for each of the heat sources by presenting the following in Table 3:

- Main data sources
- Cut off criteria
- Number of records after cut off
- Calculation parameters (for potential heat production)

For all the sources, an assessment has been made on which records are relevant to include, so that very small plants are removed from the analysis, which is here referred to as a cut off criteria. After the table, an additional explanation is given where necessary and special focus is put on the method used for the low-temperature industrial excess heat, where a new and novel methodology has been applied.

Notice that temperature differences are given in K and absolute temperatures in °C.

2.2.1. Low-temperature industrial excess heat

Industrial excess heat for DH supply is a commonly used concept in Denmark, but utilisation of low-temperature industrial excess heat using heat pumps is not yet, although there are some relatively new cases [25]. What is “low temperature” here depends on the temperature level in the DH network where the industry is located. If the excess heat temperature is higher than the temperature level in the DH network, it might be possible to utilise it without a heat pump. Most DH networks in Denmark have temperature levels below 100 °C [26] and therefore this is set as the upper temperature level for what is included in this study.

Table 1
Maximum annual excess heat potential from fuel combustion activities in Danish large-scale industrial and energy sector facilities, by DK NUTS3 regions and sectors: Thermal power (TP), Waste-to-Energy (WTE), and Industrial (Ind.).

NUTS3 regions	Facilities [n]	TP [PJ/a]	WTE [PJ/a]	Ind. [PJ/a]	Total [PJ/a]	Share [%]
Bornholm	1	–	0.1	–	**0.1**	**0.1**
Copenhagen	4	11.6	2.8	–	**14.4**	**10.4**
Funen	3	11.6	1.8	–	**13.4**	**9.7**
Copenhagen suburbs	3	9.5	3.6	–	**13.0**	**9.4**
Northern Jutland	9	15.7	3.1	4.7	**23.5**	**16.9**
Northern Zealand	3	1.6	0.9	–	**2.4**	**1.8**
Eastern Jutland	9	16.5	2.8	0.2	**19.5**	**14.1**
Eastern Zealand	1	–	1.6	–	**1.6**	**1.1**
Southern Jutland	9	23.7	3.0	2.9	**29.6**	**21.4**
Western and Southern Zealand	9	12.1	1.9	4.2	**18.3**	**13.2**
Western Zealand	4	0.8	1.5	0.4	**2.8**	**2.0**
Total	**55**	**103.2**	**23.2**	**12.4**	**138.8**	**100.0**
Share [%]		**74.4**	**16.7**	**8.9**	**100.0**	

Table 2
Number of records for different industrial type processes divided according to excess heat temperature level.

Type processes	(°C)	0–50	51–100	101–200	201–400	401–800	801–1200	1201–1600	Excl.	Total
Chemical reactions			10							**10**
Cold keeping			30							**30**
Drying			10	2						**12**
Evaporation/Condensation		189		17	7					**213**
Flue gas cooling		6	74	181	92	215	108			**676**
Freezing/Cooling			35							**35**
Furnace/Oven cooling		2	65		1	28	31	5		**132**
Process cooling		229	272	4						**505**
Product cooling			36	39	30					**105**
Sewage/Ambient water		51								**51**
Sewage/Amb. water/Process cooling		51								**51**
Waste steam			164							**164**
No excess heat activities anticipated									589	**589**
Uncertain of existing excess heat									128	**128**
Grand total		**528**	**696**	**243**	**130**	**243**	**139**	**5**	**717**	**2701**

2.2.1.1. Excess heat volumes from large-scale facilities in Denmark. In this paper, annual excess heat volumes available from large-scale industrial and energy sector activities in Denmark are assessed in coherence with the methodological framework and approach used in the Heat Roadmap Europe project [27–30], an approach detailed and fully accounted for in Ref. [21]. The explicit focus in this latter work concerned 16 selected European Union member states in the Expansion, New Development, and Refurbishment phases of DH employment on national heat markets; Danish conditions is not included in the final analysis and results presentation. In the context of the Heat Roadmap Europe assessments of excess heat activities, the main target is to establish volumetric availabilities, i.e. annual excess heat energy volumes potentially available for recovery, and to evaluate their spatial cohesion with heat demand centres, i.e. cities, towns, and large urban zones. By utilising public carbon dioxide emission data [31] and a reversed calculation sequence, involving e.g. standard carbon dioxide emission factors [32], international energy statistics [33], and default recovery efficiencies, assessments of primary energy supplies for fuel combustion activities in these sectors and, eventually, assumed annual excess heat volumes emanating from these are made plausible. However, since excess heat temperature levels is not part of these original studies – merely energy volumes – a critical source of information for the viable realization of excess heat resources is missing. In this work, which presents the maximum excess heat recovery potential for large-scale facilities in Denmark, according to the Heat Roadmap Europe assessments, an alternative and novel approach is introduced by which to associate corresponding temperature levels with these vast availabilities.

Keeping in mind that the Heat Roadmap Europe assessment of Danish excess heat volumes refers to large-scale facilities only (thermal power generation activities > 50 MW), 55 facilities are found to host theoretical (maximum) annual excess heat recovery potential of 139 PJ, as shown in Table 1. Close to three quarters of the total anticipated annual excess heat volume originates from thermal power generation activities, clearly a dominant source relative to Waste-to-Energy (WTE) incineration of municipal and industrial solid wastes (17%), and industrial excess heat (9%).

As this analysis covers only large-scale facilities, the actual potential is probably higher since small-scale facilities are not included which may as well have excess heat, although not quantified here. The 12.4 PJ (3.4 TWh) can therefore be seen as a conservative estimate of the total potential excess heat from industrial processes.

2.2.1.2. Excess heat temperature levels. A novel approach to associating temperature levels with any given or potential excess heat resource, by use of a list of "type processes", is developed on the basis of Swedish experience reported in Refs. [34], and a combination of complementary sources with respect to temperature levels for each type process [35–41]. Hereby all current Danish economic activities, by European Nomenclature of Economic Activity (NACE) class codes (level 4), registered in the European Pollutant Release and Transfer Register (E-PRTR), are allocated one or several type processes and corresponding temperature levels. As can be seen in Table 2, this approach has rendered a matrix of 2701 unique potential Danish excess heat resources.

Table 3
Summary of data sources, cut-off criteria, records after cut-off and calculation parameters for the selected heat sources.

	Low temperature industrial excess heat	Supermarkets	Waste water	Drinking and usage water	Ground water	Lakes	Rivers	Sea water
Main data sources	Described in Section 2.2.1	Overskudsvarme i dagligvarebutikker (Excess heat in supermarkets) [43]	Data set on measured discharge of water from waste water facilities [51]	The Jupiter Database on boreholes and geological measurements [45]	The online available background data for the GEUS project called "Limitations of ground water availability in Denmark" [47]	Background data from municipal water plans [52]	Background data from municipal water plans [52] Report about water flow in Danish rivers [49]	Denmark's Administrative Geographical Division [23]
Cut-off criteria	1) Above 100 °C 2) CHP, waste incineration and thermal power plants 3) Waste water cleaning facilities	The smallest identified category of supermarkets removed	Below 1 GWh/year	1) Below 1 GWh/year 2) Registered as "inactive" 3) Water type other than ground water 4) Catchment purpose other than "water supply plant" or "not reported"	–	Less than 1 km^2	Type 1 and 2 rivers as defined in Ref. [53]	–
Records after cut-off	178	2272	372	393	2771	87	40 (river segments)	1
Calculation parameters	–	See full calculation method in Ref. [43]	Cooling of source: 6 K. Suggested in Ref. [19]	1) Cooling of source: 5 K 2) Utilised share of water catchment permit: 80%	1) Production potential: 1.43 MW/facility 2) For DH network> 1 km^2: 1.43 MW/km^2	1) Cooling of source: 2 K 2) Lake depth: 2 m	1) Cooling of source: 2 K 2) River flow utilization: 10%	–

Table 2 shows that about half of the identified processes with expected excess heat are between 0 and 100 °C, which is here considered “low temperature”. Based on this data set, the mapping is done and the cut off criteria applied. CHP, TP (Thermal power), and waste incineration plants are removed because of the scope of the study, and waste water treatment facilities are removed since these are covered in Section 2.2.3. This leaves 178 unique industrial facilities with low-temperature excess heat potential.

2.2.2. Supermarkets

Supermarkets are included as a heat source in this study because of their need for cooling of goods, which generates excess heat. The special benefit of this is that the heat pump is already in place and if adjusted correctly, it can supply DH as well as cooling for the refrigeration [42]. These can potentially be very cost efficient to include for DH producers as the main investment of the heat pump is already made in the cooling system in the supermarket.

The background data set for this heat source category has been disclosed to the authors of this paper by the authors of another study who did thorough data collection and treatment on this particular issue. This comprises an extract of the Central Business Register (CVR register in Danish) which is sorted to isolate the supermarkets. These are grouped into typical sizes and associated with average heat production potential. The method is described in detail in Ref. [43].

2.2.3. Waste water

Cleaning of sewage and waste water is an activity that produces a relatively constant water flow throughout the year, with a higher temperature than the ambient environment, and there are approximately 1400 facilities in Denmark [19,44]. The temperature of the discharged water varies from summer to winter but generally does not go below 9 °C in the winter [19,44]. It is assumed that water cooling will be possible all year round and the energy potential is calculated based on this assumption.

The data on which the analysis is based consists of registrations of amounts of discharged water from all of the registered waste water treatment plants in Denmark made by the Danish Nature Agency and the data has been disclosed to the authors of this paper for the period 2011–2013.

2.2.4. Drinking and usage water

Drinking and usage water is included even though it is still unknown how and in which cases it can work as a heat source. The reason is that if drinking water is cooled before distribution and then needs reheating for its specific purpose, e.g. showering or dishwashing, the benefit is reduced [44]. According to [44], an ongoing assessment is currently quantifying this problem. However, even though the quantity is uncertain, it will have some potential as not all water consumption needs to be heated. The temperature of ground water, which is used for drinking and usage water, is 8–9 °C throughout the year [44].

For the mapping of drinking and usage water, the Jupiter database has been used. This documents all kinds of drilling and boreholes in Denmark, including those for water catchment facilities. Here the coordinates for the plants and the annual permitted water catchment amount is utilised [45]. It has not been possible to find measurements on water catchment in combination with the water catchment location, so it has been assumed that 80% of the permitted catchment amount is utilised.

2.2.5. Ground water

In technical terms ground water as a heat source is identical to drinking and usage water. The main difference is the presence of the infrastructure and certainty of water resource availability. This will assumingly make the costs and risks, related to the investment and operation, of utilising ground water higher than drinking water [44]. After the ground water has been cooled down in the heat pump, it can either be let out into surrounding surface water, let out underground to seep down through the ground towards the ground water reservoirs or directly reinjected into the reservoir. The solution will depend on the local environment and restrictions in the ground water reservoir [46].

The data set consists of all the registered ground water reservoirs in Denmark, of which some are used for drinking water and others do not have the sufficient water quality for this purpose. Here, all the identified reservoirs are included because a water quality too low for drinking purposes does not exclude it from being used as a heat source [45,47].

The DH plant in Gammel Rye in Denmark has a heat pump system installed using ground water as its heat source. The total thermal output of this heat pump system is 2 MW with an average coefficient of performance (COP) of 3.5, which means that it consumes 0.57 MW electricity and 1.43 MW heat from its heat source to produce the output [48]. The value from this real case is used in the calculation of the total potential for the country. It is assumed that all DH networks located within an area with ground water available according to the above mentioned, can have at least one heat pump system with the same capacity as the one in Gammel Rye. In DH networks with larger areas than 1 km^2, which applies to 51 out of the 403 networks, it is assumed that one facility like the mentioned case can be installed per km^2.

2.2.6. Rivers

Denmark does not have large rivers, but even the ones that exist can contribute as heat sources. The main barrier is the temperature level, which is lower in the heating season, as well as legislative regulations prohibiting cooling the water to less than 2 °C and setting a maximum temperature difference from inlet to outlet of 5 K [44]. This means that the heat pump should be supplemented by other heat sources and maybe a seasonal thermal storage.

The geographical data on the rivers is from the online available background data for water plans. Here only the largest category of rivers (category 3) is included. The flow in the rivers is from Ref. [49] where the 10 largest rivers are listed. For the smaller rivers, the average flow is assumed to be 5 m^3/s.

2.2.7. Lakes

For the lakes, the same temperature limitations exist as for the rivers described in Section 2.2.6. As is the case for the rivers, an increased risk of icing on the water is present in the cold months on the lakes because of the lack of flow [44].

To calculate the potential heat production of a lake, it is assumed that the total water volume of the lake can be cooled 2 K once every year on average. The volume of the lake is here defined as the geographical area of the lake multiplied by a depth of 2 m. This is seen as a conservative estimate, but it should be noted that it may not be possible to utilise this energy potential much in the winter since the water cannot be cooled below 2 °C.

2.2.8. Seawater

Seawater is almost without capacity limits for the DH networks located on the coast, compared to the heat demands for DH. The most important limitation to this heat source is the temperature level as for lakes and rivers, but in contrast, however, it might be an option to cool the sea water below 2 °C, using the phase change energy and letting out an ice-slurry like has been the case in the Augustenborg DH system in Denmark [50].

Potential energy production by use of sea water as a heat source has not been calculated here, but as for the other heat sources it is

Table 4
Summary of analysis results for availability and potential heat volumes of the different heat sources. *This indicates a value calculated in Ref. [21] for large-scale industry.

Heat source	Geographical availability of heat source (%)		Potential heat volumes (TWh)
	To number of DH networks	To total heat demand	
Low-temperature industrial excess heat	17.1	64.6	3.4*
Supermarkets	61.5	95.8	0.4
Waste water treatment	34.5	68.0	2.9
Drinking water	31.0	78.8	0.8
Ground water	98.8	99.8	6.9
River	8.4	30.7	3.2
Lake	7.7	21.9	0.7
Sea water	28.8	65.3	–

registered which DH networks are near the coastline. To determine this, the geographical dataset "Denmark's Administrative Geographical Division" is used, which describes the geographical location of the coastlines, municipalities and others [23].

3. Results

The main results of the analysis are presented in Table 4 for both the geographical availability and the potential heat volumes. The results are explained further in the following sections.

3.1. Geographical availability

The results shown in the second and third columns under "Availability of heat sources" in Table 4 show a summary of the geographical availability of the different heat sources for the DH networks. The availability for the number of DH networks shows the percentage of DH areas in Denmark having access to the given heat source. The values under "To total heat demand" show how large a share of the total DH demand in Denmark is represented in the DH networks with access to the given heat source. It does not show how large a share of the DH demand can be covered by these heat sources. This question needs to be subject to another study in order to be answered.

It can be seen in Table 4 that for all the heat sources the share in 'To number of DH networks' is lower than the share in 'To total heat demand'. The reason is that there are in general more heat sources located near cities and more heat sources are located close to larger cities than to smaller ones and since the larger cities also in general have larger demands, the availability to the total demand is bigger than to the number of networks.

3.2. Potential heat volumes

The fourth column of Table 4 shows the summary of the potential heat volumes of the heat sources accessible to the DH network. This does not include the heat sources outside the 500 m radius of the DH networks, and practical and case specific barriers for utilisation of the heat sources are not included either. This means that in reality some of this potential may not be feasible to utilise.

The value for low-temperature industrial excess heat is taken from another study, as indicated in the table. This value covers large-scale facilities which are registered in the E-PRTR and therefore includes some excess heat from thermal heat and power production as well as high-temperature sources. On the other hand, small-scale industries with excess heat are not included. Therefore, the potential cannot be compared to the other values, but it indicates the scale of potential heat volumes from this source.

3.3. Regional potential

Fig. 3 shows the results in a map. It can be seen how the identified heat sources relate to the DH demands for each municipality in Denmark. It reveals a geographical difference between the heat sources and DH demands where the municipalities with the bigger cities have lower amounts of heat sources compared to the DH demands. The municipalities of four out of the five biggest cities in Denmark (Copenhagen, Aarhus, Aalborg and Esbjerg) are in the lowest category, where Odense is in the second lowest category. The municipalities in the highest categories, on the other hand, are areas with relatively low population densities and no big cities.

4. Discussion

The results show that there are potential heat sources relevant for heat pumps for DH in all parts of Denmark. It also shows that the potential energy volumes of these heat sources are not distributed proportionally to the DH demands. This means that some areas have better potential for utilising heat pumps for DH than others. This is discussed in the following in relation to two analyses of scenarios for 100% RE for Denmark. Lastly, some important uncertainties will be discussed.

4.1. Potential and distribution of heat sources

Coherent Energy and Environmental System Analysis (CEESA) is a project carried out in cooperation between researchers from different universities in Denmark. The project aims at assessing different scenarios for how all energy demands in Denmark in 2050 can be supplied with 100% RE in a sustainable way. In the CEESA 2050 Recommendable scenario, 34% of the DH demand is covered by supply from heat pumps [54] equivalent to 13.6 TWh/a, with a majority on the central DH networks (in the bigger cities). In another study from the DEA analysing different paths for Denmark towards 100% RE in 2050, the supply from heat pumps ranges from 8 to 33% in the different scenarios, equivalent to 2.3–8.8 TWh/a mainly depending on the consumption of biomass resources [9]. In contrast to the CEESA project, the DEA study is assuming a different development in DH demand and has a majority of heat pumps in decentralised DH networks.

The heat volumes identified in this study sum up to 14.9 TWh/a, excluding low-temperature industrial excess heat and sea water, as seen in Table 4. This table also excludes the contribution from electricity reflected in the COP of the heat pump. This means that the total volume of heat potential is big enough for what is assumed in even the CEESA study with the highest demand for heat sources. As can be seen in Fig. 3, the areas with the larger cities have lower shares of heat source potential relative to their demands compared to the areas outside the bigger cities. This means that in case the majority of heat pumps are located in the bigger cities, the pressure

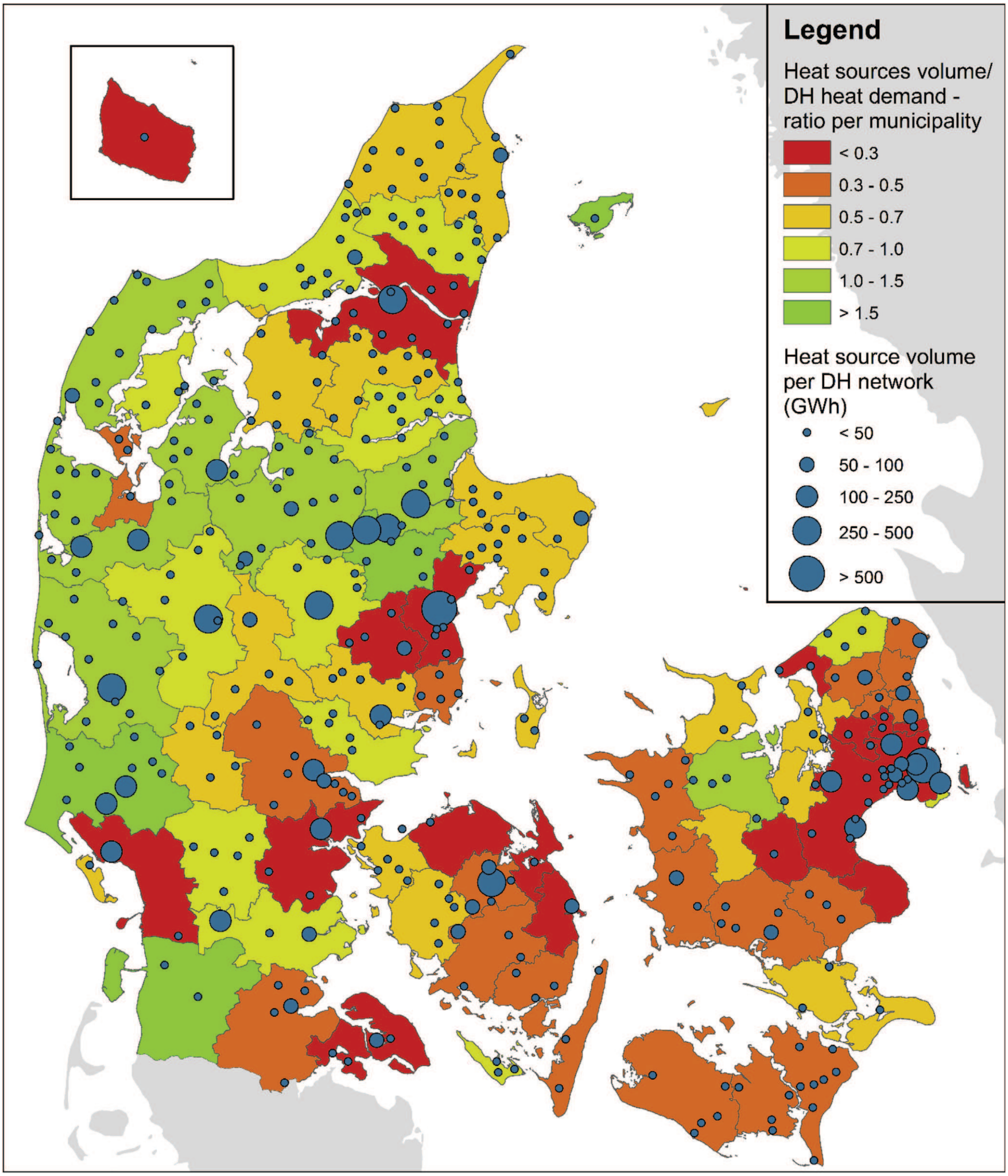

Fig. 3. Map of heat sources in Denmark relative to heat demand summarised per municipality. The blue circles indicate location of DH networks and the corresponding heat sources. Low-temperature industrial excess heat and seawater are not included.

on the heat sources will be higher, and more ambient temperature heat sources, e.g. sea water, will probably be needed in this case. The opposite situation occurs if the heat pumps are mainly located in the decentralised DH networks in the smaller cities and thereby more proportional to the distribution of the identified heat sources.

4.2. Uncertainties of industrial development and local barriers

This study is based on a relatively large number of different data sources to characterise the potential of the different heat sources. This also entails some uncertainty since the different data sources are of different quality and level of detail, but an effort has been made to get sources of an acceptable level for each specific purpose. Two important specific areas of uncertainty are discussed here and the consequences assessed.

The one is the uncertainty of how the industrial sector will develop. If many of the industries currently having excess heat relevant for DH close or move to other countries, this potential will be reduced, and vice versa if new industries start up. Energy efficiency measures can also influence the potential both positively, if internal savings create a bigger excess for DH, or negatively, if energy efficiency reduces the energy consumption and excess heat.

The other important uncertainty is linked to how much of the potential heat sources cannot be realised, because of practical, environmental, technical, or other barriers relevant in each specific case. These are hard to predict, but will be revealed in a case specific screening for potential heat sources in a given area. One barrier might also be the temporal distribution of the given heat source. For example, if a specific heat source is only available in the summer for a DH network with its demand already covered during this season, then it might only be relevant in a system with a seasonal thermal storage.

Since some heat sources are more attractive than others, have higher temperatures, lower investment costs etc., the most feasible sources will presumably be realised first. This will in many cases be the excess heat from industry followed by some of the other sources. The ambient temperature heat sources are seen as the least feasible sources and are expected to be chosen as the last alternative, possibly to supplement other sources. This means that if there is more industrial excess heat available in a given DH network, the need to use ambient heat sources is reduced and vice versa. The same applies to the uncertainties related to the local barriers, so that less locally available heat sources increase the demand for ambient temperature sources.

5. Conclusion

It can be concluded that there are heat sources available everywhere in Denmark and 398 out of 403 DH networks, have access to one or more of these. Ground water as a heat source shows to have the highest both geographical availability and potential heat volume. The supermarkets are noteworthy with a relatively high geographical availability, but a low potential heat volume and rivers with a relatively low geographical availability, but a high potential heat volume. It can also be concluded that the heat sources available do not geographically match the DH demands. This is mainly the case for the bigger cities in Denmark, where the potential heat sources per heat demand are significantly lower than in the rest of the country.

To be able to use the information provided in this study for national scale scenarios or similar, the annual and hourly availability should be studied more carefully. It is important to know the temporal details and availability of the heat sources to be able to analyse these in a full-scale energy systems perspective, where dynamics between different sources of energy and technological capacities are crucial. The costs of the different technologies necessary for the different applications of the heat pump should also be studied further. By including these elements, it will be possible to analyse and recommend, with a greater level of detail, which heat sources will be preferable and where.

The concrete results of this study are only relevant in the Danish context. The tendency found in the analysis, that the heat sources connected to the cities are not alone enough to cover the heat demands in the cities, will apply for countries in similar climate zones and the method is applicable for any context.

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PAPER 4

Choice of insulation standard for pipe networks in 4th generation district heating systems

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Research Paper

Choice of insulation standard for pipe networks in 4th generation district heating systems

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HIGHLIGHTS

- New method for assessment of the insulation level for district heating is suggested.
- It combines a detailed heat loss analysis with an integrated energy system analysis.
- The method can be used to evaluate socioeconomic and energy system consequences.
- The method is presented and its application demonstrated for the case of Denmark.

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ABSTRACT

Reducing heat losses from the pipe networks in district heating (DH) systems is one of the main challenges when developing DH in the future. Fourth generation DH is a concept that defines the role of DH in future smart energy systems as an integrated part together with smart electricity grids and smart gas grids. Improving DH pipes by improving the insulation standard results in decreasing the heat and temperature losses from the pipe networks. When reducing heat losses from DH pipes, there is a trade-off between the increasing cost of pipe insulation and the associated savings in the heat supply system. This study presents a methodology to describe this balance for a specific case and its application for the case of Denmark.

The methodology presented consists of a techno-economic analysis in two steps. In the first step, a DH grid model is used to assess the reduction in grid losses by implementing different pipe insulation standards. In the second step, the specific grid losses found in the first step are analysed in an integrated energy systems model where all main energy sectors and their interrelations are included. The outcome of the study can provide decision support when planning investments in DH systems today and in the future. The results from the case of Denmark shows that pipes with higher insulation standard (series 3) is generally preferable, but the highest insulation standard available today (series 4) might be preferable in the future if fuel prices or increase or investment costs decrease.

1. Introduction

Heat loss from district heating (DH) networks is a problem, but this is also inevitable. Reducing heat losses will reduce the primary energy demand and thereby fuel consumption and the need for infrastructure investments [1]. On the other hand, reducing heat losses is also associated with an additional economic cost and this makes a balance between heat losses, costs and fuel consumption [2]. This balance is important to assess when planning for DH networks because investments in DH network and infrastructure are long-term investments that may last more than 40 years.

Reducing heat demands in DH systems in general have been shown in several studies to be important in the future because of limited resources when fossil fuels are no longer available [3,4]. It has also been shown that DH systems in the future will have an important role even with substantial heat savings in Denmark [5,6] as well as the EU [7]. The heat losses from the pipe networks are an important figure in this connection because this accounts for a relatively large share of heat production.

Dalla Rosa et al. [8] divide the variables affecting heat losses into four categories: Operational data, thermal conductivity, geometry of pipes and pipe arrangement such as single pipe, twin pipe etc. Several different strategies have been suggested to reduce heat losses;

Abbreviations: RE, Renewable Energy; DH, District Heating; CHP, Combined Heat and Power; DHN, District Heating Network; CEESA, Coherent Energy and Environmental System Analysis; 4DH, 4th generation District Heating; DN, Nominal Diameter.

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reduction of network temperature level [9], design of pipe network layout [10,11], choice of pipe types [12], operation and management [13] and changing the insulation thickness or material of the pipes [14,15]. General for the studies suggesting these strategies is that they have applied analyses of isolated energy systems and only considering the heat flows and not the rest of the energy system, such as electricity, fuel production or industry.

This study suggests and demonstrates a methodology to assess the balance between reductions in heat losses and socioeconomic costs considering all energy sectors. The methodology is combining two analyses where the first is a detailed heat loss analysis of different alternative pipe systems and their heat losses considering the variables described in [8].

The second part is an integrated energy systems analysis taking all substantial sectors within energy and the dynamics between them into account. The savings in fuel and costs do not decrease as a linear function with the heat losses, but depends on the changes in system dynamics with lower heat losses, and the combined analysis is therefore important and can provide valuable information when planning for short and long-term investments in DH systems.

The paper is organised as follows. Section 2 presents the theoretical concept Smart Energy Systems and how 4th generation DH is an important part of future integrated energy systems. In section 3 the methodology of the two-part analysis is presented in details. In sections 4 and 5, a case study is presented and elaborated. Lastly, in section 6 the suggested method is discussed and a conclusion given.

2. Smart energy systems and 4th generation district heating

Smart energy systems is a concept that highlights the importance of integrating energy sectors concurrently with the introduction of RE production [2]. The electricity, heating, fuel, industry and transport sectors need to be more integrated to be able to accommodate higher shares of e.g. wind or solar power. Lund has defined smart energy systems in Reference [16] as the combination of 1) Smart electricity grids, 2) Smart thermal grids and 3) Smart gas grids. The imbalance between the supply from renewables and the demand must be coped with by dynamic interaction between the components in the energy system. Examples are short-term flexible CHP plants [17], large heat pumps for DH and cooling [18], electrolysers and large-scale fuel production for transportation [19] or energy storage systems [20].

Fig. 1 shows the difference between a conventional energy system (left) and a smart energy system (right) on a conceptual level. It shows that the smart energy system has higher penetration of wind power, is more integrated between the energy sectors and much less dependent on input of fuel.

DH is a central part of a smart energy system in the Danish context, where heat demands cover a large proportion of the primary energy demand. DH is important because it enables the utilisation of heat sources that would not be feasible to utilise with individual heating systems. The ability to make use of excess electricity production from e.g. wind turbines in heat pumps in combination with thermal storage for the heating supply is another important contribution to the development towards a RE system [1].

CHP plants, together with fuel boilers, are currently the main contributors to DH supply in Denmark, but in the future in a system based on 100% RE, the supply from these can be replaced with industrial waste heat, ambient heat sources harnessed by heat pumps, solar and geothermal heat among others. To integrate these new heat sources in a feasible way, however, the DH systems have to change compared to the system of today [1].

In general, the heating demand should be reduced to approximately 50% of its present level [21]. At the same time, DH will be expanded to cover areas that currently have their demand covered by natural gas boilers, oil boilers or electric heating [7,22]. This means that DH systems should be planned and designed to accommodate lower heat demand densities, but with an increasing number of consumers. One important point here is that heat losses from the pipes need to be significantly reduced, by lowering the temperature in the network and improving the pipes' insulation and network layout [23].

3. Methodology

In this section, the suggested method for assessing the feasibility of different types of DH pipe systems is presented.

3.1. Method structure

The purpose of this method is to assess different insulation standards to provide an input for decision support for a planning or policy process related to investments in DH pipe infrastructure. This method combines a detailed heat loss analysis of DH networks with an integrated energy systems analysis.

Fig. 2 illustrates the overall structure of the methodology proposed in this study, where three alternatives for the existing (reference) pipe networks are evaluated.

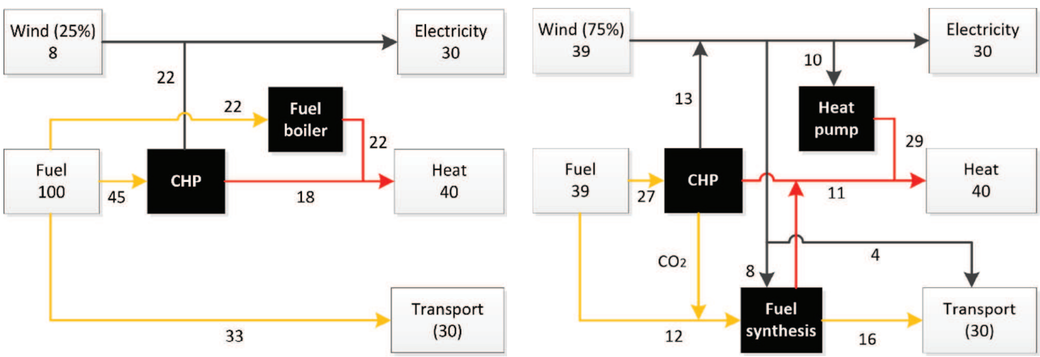

Fig. 1. Conceptual flow diagram of two energy systems. White boxes indicate supply (left) and demand (right) where black boxes indicate conversion technologies. Arrows indicate energy flows where black is electricity, red is heating and yellow is fuel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

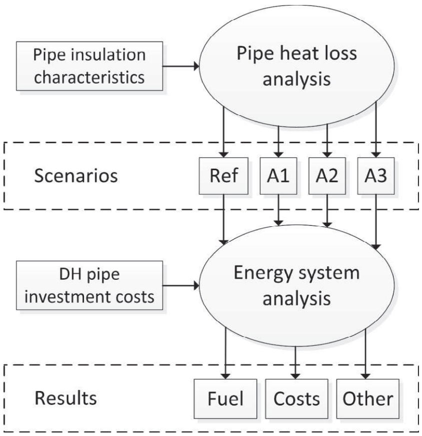

Fig. 2. Diagram showing the structure of the method components. The circles illustrate the two parts of the analysis; the pipe heat loss analysis and the energy systems analysis. A1, A2 and A3 indicate alternatives to the reference.

The two tools for modelling the district heating network (DHN) operation and energy systems are fundamentally different. The DHN modelling tool focusses on simulating the flow and temperature changes in the pipe networks. The energy system model on the other hand do not consider the actual pipes, but model DH as a supply system and heat demands with a loss in between to represent the DH pipe network. The key figures that integrate the two models are the heat losses for the analysed scenarios which is an output from the DHN model and an input for the energy system model. See further details on the two models in sections 3.2 and 3.3, and in Figs. 4 and 5.

The heat loss analysis is performed for a concrete DHN. In the energy systems analysis the values are up-scaled to cover all DH networks in the country. The results are in the form of *reductions in heat losses* given as a share of the existing heat loss instead of specific heat losses. This means that values are independent of the specific DHN, but it is necessary to use an actual DHN as the point of departure because of the combination of different pipe diameters in such network. When applied to the large-scale systems, the reductions in the heat losses can be applied to the actual values in the analysed region.

3.2. Heat loss analysis and the DHM model

To analyse different scenarios of lowering the heat losses in DHNs, it is important to have a model, which reflects the dynamics of the DHN. To study the DHN behaviour, both the dynamics of consumers and the dynamics of distribution networks and time delays in the network have to be studied. The difference between the DH water temperature and its surrounding temperature (soil) is the main cause of heat loss in DHNs, but the pipe dimensions and insulation material also affect the heat loss [24].

To study the transient temperature changes, one approach is a lumped system analysis where the variation of the temperature within the body is neglected. It is applied for small bodies of highly conductive materials [25]. Such approach does not provide the required level of accuracy for simulating the heat transfer in insulated pipes buried under ground as the variation of temperature with both time and position matter and therefore, a more complex model is needed. To model the transient heat transfer problems numerically the finite element method is applied where both discretisation in time and space is required. It is described in section 3.2.1.

3.2.1. Model design

A tool for thermal-dynamic modelling of DHNs with branched topologies developed in Matlab is applied here. It is documented in Reference [26]. Here, it is suggested to use a so-called pseudo-dynamic model where the principle is to determine the flow and pressure by means of steady state calculation whereas the temperature is calculated dynamically. This approach has been shown to provide good predictions of operation data and heat losses.

The network is modelled in regular time intervals (of an hour or less). In each time interval the flow is assumed steady state and is calculated based on consumers' heat load. The temperature changes are calculated dynamically in the number of time steps in each time interval, and are used as an initial condition for calculating the new flow rate for the next flow calculation [24].

In the finite element method used in the model design, initially each pipe is divided into number of elements in an axial direction. The length of the pipe elements depends on how accurate and detailed calculations are needed. Then each pipe element is divided into a number of coaxial sections including water, pipe, insulation, jacket pipe and a cylinder of soil surrounding the pipe. Fig. 3 presents an illustration of the pipe elements and a coaxial cross-section of an element.

A heat balance equation describes the heat transmission from the heat capacity of each pipe section. The numerical implicit method is applied to calculate the heat balance equations where all the heat balance equations in each element are solved at the same time. To calculate the length of the time steps, the so-called Courant number is used. This should be exactly one when the implicit method is applied [24,25]. The Courant number is calculated as given in Equation (1):

$$C = \Delta t \times v / \Delta x, \quad C = 1 \rightarrow \Delta t = v \times \Delta x \tag{1}$$

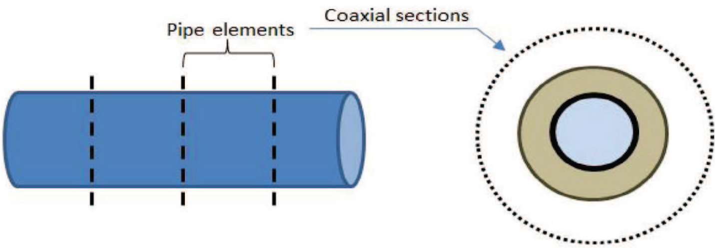

Fig. 3. The illustrations present a pipe segment divided into the number of elements (left figure) and a pipe element divided into the number of coaxial sections including water, pipe, insulation, jacket pipe and a cylinder of soil surrounding the pipe (right figure).

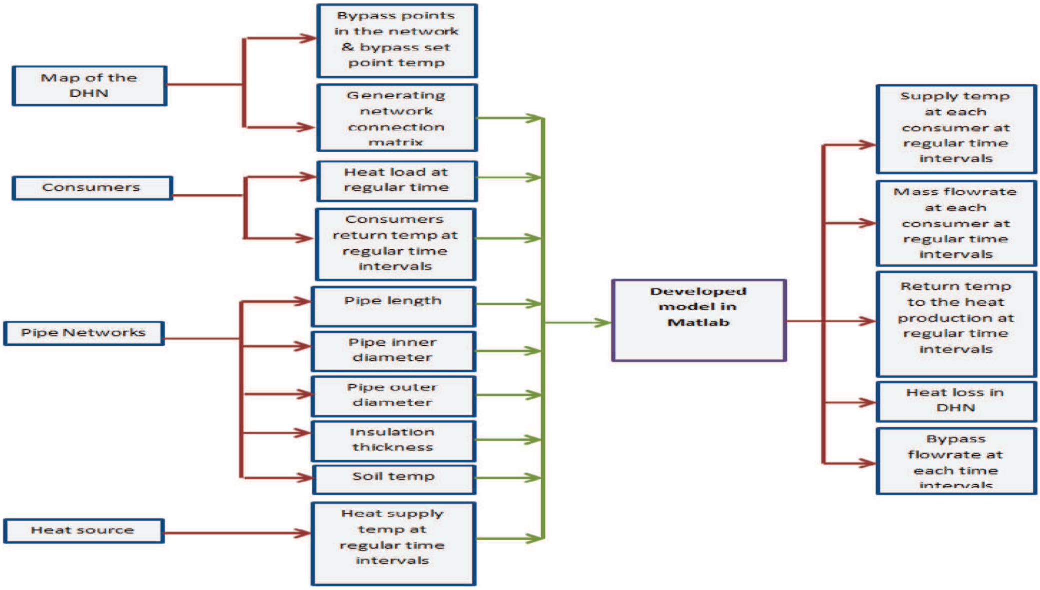

Fig. 4. The simplified diagram shows how the DHM model works; the input variables of the model (left) and the output of the model (right) are presented.

C is the courant number, v is the flow velocity in the pipe in $[\frac{m}{s}]$, Δt is the time step length in $[s]$ and Δx is element length in $[m]$. For a predetermined Δx and v, the Δt is calculated. The number of time steps (n_t) in a time interval (t_{int}) is given in Equation (2):

$$n_t = {t_{int}}/{\Delta t} \tag{2}$$

3.2.2. Model application

The DHM model uses the supply temperature from the heat production plant, the heat demand and return temperature from each consumer. The model then calculates the temperature losses at each pipe segment through the network, the supply temperature and the flowrate of each consumer at the corresponding time intervals. Based on this, the total heat loss from the system is calculated and when different pipe insulation standards are implemented in the model, the different relative heat losses can be observed.

The developed model is applied to and validated against the Termis model for a DHN in Studstrup, Denmark, to make sure that the prediction of the model is accurate enough, which is described further, together with the model characteristics, its limitations and assumptions, in Reference [26]. Fig. 4 shows the basics of how the DHM model works and the input–output flow can be seen.

3.3. Energy systems analysis and the EnergyPLAN model

The purpose of the energy systems analysis is to put the results of the heat loss analysis into the context of a full-scale energy system and to analyse the system impacts and changes between the different scenarios. The tool needs to be able to analyse all the substantial sectors of the energy system and the dynamics between the sectors. It is also important that the analysis is performed with a high time resolution to capture seasonal and daily changes and the influence of energy storages.

For this study, the EnergyPLAN model is chosen. It is a deterministic input–output model that simulates the operation of a user-defined energy system for every hour of one full year and is designed to analyse the impact of large-scale integration of new technologies, RE sources or technological changes. The model is structured according to energy sources, conversion and storage technologies and energy demands, as shown in Fig. 5. All the energy sectors (electricity, heating, transport, industry and others) are integrated with one another, as suggested in Section 2 about Smart Energy Systems, to be able to identify interaction and potential synergies between the sectors. The model is documented in Reference [27].

The inputs to EnergyPLAN consist of a definition of demands, available conversion technologies in the given energy system and the available energy sources. EnergyPLAN seeks to meet the demand in the most efficient way, given a number of regulation criteria and strategies. It uses the available conversion technologies, storages and energy sources following a given merit order. For example, wind power or waste incineration will be used before starting the CHP plants.

The total annual cost of the system is the sum of annual investment costs, fuel costs, fixed and variable operation and maintenance costs and CO_2 emission costs. Annual investment costs are calculated as the annuity using investment cost, technical lifetime and a discount rate.

The EnergyPLAN tool is relevant to apply to this study, in particular because reduced grid losses from DH pipes will impact the supply system differently between hours and months depending on changes in heat demand, wind power production, seasonal changes in available heat sources, and the general system configuration. Therefore, an advanced energy systems analysis is required to determine the total system benefit.

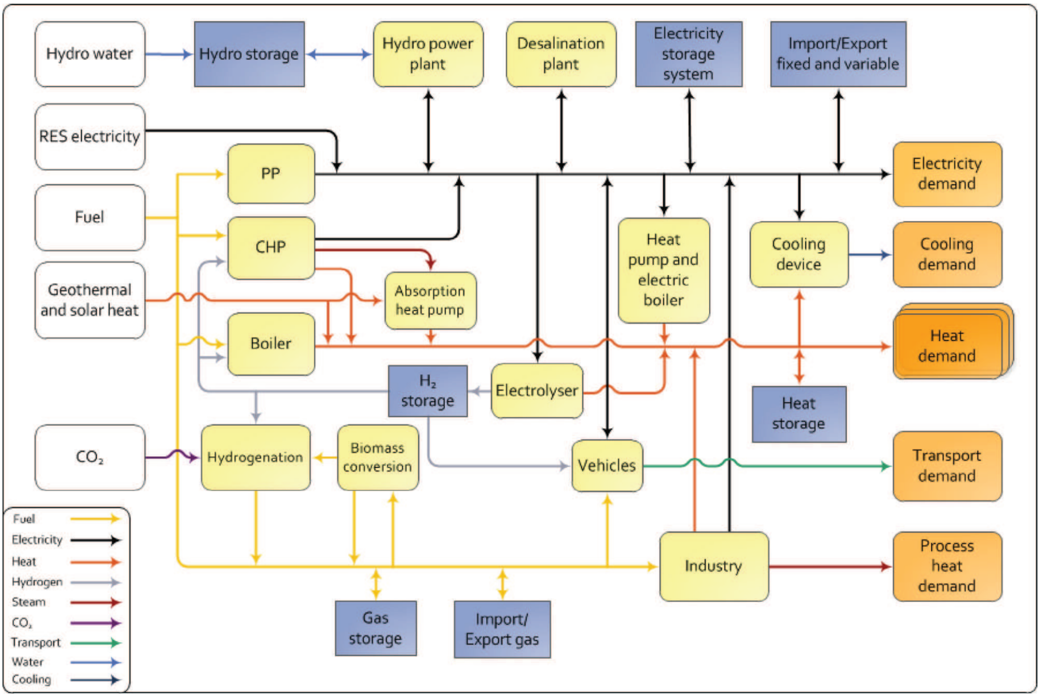

Fig. 5. Simplified flow chart illustrating energy sources (white), conversion technologies (yellow), storage and exchange options (blue) and demands (orange) in EnergyPLAN. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Scenarios and specific assumptions

4.1. Definition of scenarios

The scenarios in this study are defined by the pipe insulation series, which goes from series 1 to series 4. The reference scenario is a combination of series 1 and series 2 representing the current situation in Denmark. The alternative scenarios are assumed to be purely series 2, 3 or 4. The specifications of the pipe series are presented in section 4.2. The main variables between the scenarios are:

1. The total pipe investment costs.
2. The pipe heat losses.

The losses and costs for the different scenarios in the energy systems analysis are applied to two different energy system models of Denmark: one for 2013 based on historical data and one representing a smart energy system for 2050 developed in the project called Coherent Energy and Environmental System Analysis (CEESA). These two are further defined in section 4.5.

The results of the analyses are total fuel consumption and total energy system costs.

4.2. Specifications of pipe insulation series

In this study, four pipe series have been analysed which includes series 1 to series 4, hereafter referred to as S1 to S4, where S1 has the lowest and S4 the greatest insulation thickness. All the pipes are pre-insulated steel single pipes with polyurethane foam as insulation and polyethylene as outer casing (jacket pipe).

Table 1 presents the outer diameter of the pipes and thereby the thickness of the insulation and the corresponding prices for different insulation series. The price consists of the cost of digging, road recovery, pipe work, pipe material and insulation material for pipes buried at a depth of 80 cm.

4.3. Studstrup DHN – the reference area

The DHM is applied to a DHN in Studstrup. Studstrup is a suburban area in Aarhus, Denmark. Fig. 6 shows a map of the Studstrup DHN. The DHN trench length is 6937 m, and serves 321 consumers

Table 1
Applied pipe specifications for insulation thickness [28] and pipe costs [29] used in the heat loss analysis for each nominal pipe diameter (Dp) in four pipe series (S1–4).

		Insulation outer diameter (mm)				Pipe costs (€/m)			
Pipe no.	D_p (mm)	S1	S2	S3	S4	S1	S2	S3	S4
DN20	26.9	90	110	125	140	464	481	496	512
DN25	33.7	90	110	125	140	464	481	496	512
DN32	42.4	110	125	140	160	467	481	496	514
DN40	48.3	110	125	140	160	486	500	516	533
DN50	60.3	125	140	160	180	504	520	538	557
DN65	76.1	140	160	180	200	511	539	549	569
DN80	88.9	160	180	200	225	548	559	590	615
DN100	114.3	200	225	250	280	631	656	686	715
DN125	139.7	225	250	280	315	723	751	782	815
DN150	168.3	250	280	315	355	798	827	862	899
DN200	219.1	315	355	400	450	888	924	965	1010

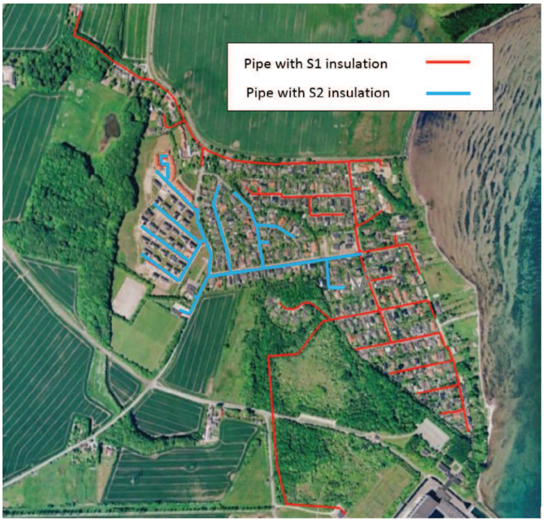

Fig. 6. Map of the Studstrup area with indication of the DHN trenches.

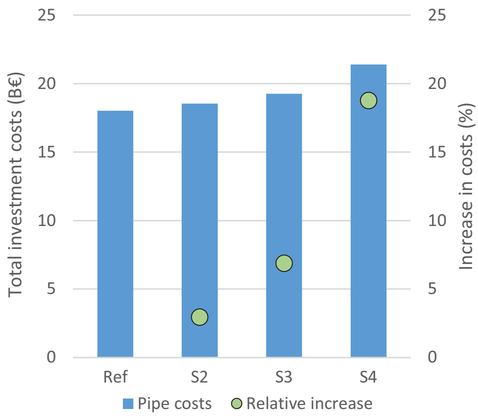

Fig. 8. Total investment costs of pipe systems in the different scenarios in the Reference 2013 system and the relative increase in pipe investment costs in the alternative scenarios compared to the reference.

and the network consists of series 1 and 2 pre-insulated single steel pipes.

The available heat demand data for the analysis are aggregated in eight time periods. Fig. 7 presents the heat load duration curve for Studstrup DHN. To obtain the consumers' heat load at each time step, the consumer's average annual heat load is adjusted by applying load factors to the corresponding time periods. The same procedure is employed for calculating return temperatures. The soil temperature and the supply temperature from the plant are also allocated for each time period. The result is based on a calculation in hourly time intervals for one full year.

4.4. Investment costs of pipe system

The total investment cost for the DH pipes is a central parameter and the definition of these has a large impact on the results of the analysis. Here the applied costs are presented and explained.

A total investment cost for all DH pipe networks in Denmark is needed in the analysis to assess which pipe series will be the most feasible in general.

The values are calculated based on statistics from the Danish District Heating Association on data annually collected from their member companies [30]. This shows that in total there are 30,500 km pipes in trench length (combination of supply and return pipe). Combined with the system cost of the DH system in the Studstrup case for the four scenarios presented in subsection 3.4, this gives a total cost of the DH pipe systems in Denmark.

It is assumed that the pipes are replaced at the end of their technical lifetime in any case, and therefore the differences between the analysed scenarios define the marginal system cost of potentially choosing a more expensive pipe series in case of replacements.

Fig. 8 illustrates the total investment cost of the DH systems in Denmark and the relative increase in cost compared to the reference scenario. The S3 and especially S4 pipes are new and not commonly used yet. Therefore, a drop in costs might take place in the future if the technology wins more market shares.

4.5. Energy system analysis assumptions

The four scenarios are implemented into two energy systems models: one of a reference for Denmark in 2013 (Reference 2013) and one of a potential future system for Denmark based on 100% RE, the CEESA 2050 model (CEESA 2050). The analysis is performed in both of these systems to assess the current potential and the future perspective of the different pipe series, since these are long-term investments. The Reference 2013 is based on national energy statistics and the CEESA 2050 is designed in connection with

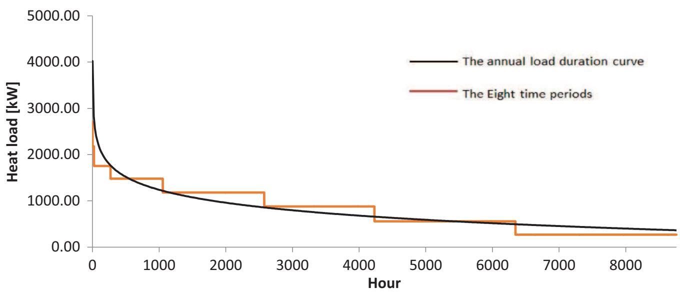

Fig. 7. Load duration curve for Studstrup district heating network in 2012.

Table 2
Main assumptions for the two modelled energy systems used in the scenario analysis.

Parameter	Reference 2013	CEESA 2050	Unit
Electricity demand	33.65	24.67	TWh
District heating demand	30.20	31.93	TWh
Individual heating demand	19.87	9.30	TWh
Wind capacity on- and offshore	4,802	10,618	MW
Solar PV	478	5,000	MW
Total power plant capacity	7,175	10,333	MW
CHP electric capacity	7,830	4,445	MW
CHP thermal capacity	12,302	2,534	MJ/s
Central heat pump electric capacity	0	900	MW
Individual heat pumps	0.86	8.37	TWh
Waste input for incineration	10.45	4.16	TWh
Input from industry and waste heat	1.73	6.05	TWh
Electricity for transport	0.38	8.22	TWh

the CEESA project. The main assumptions of the two systems are presented in Table 2.

The two systems are different in many ways, but the most important differences will be elaborated here. Total heat demands have been reduced in the CEESA scenario, and a lot of the individual heating has been connected to DH systems. In the supply of DH, CHP and waste incineration have much smaller shares in the 2050 system, where a variety of new heat sources is integrated, such as heat pumps and industrial waste heat. The CEESA project and its assumptions are elaborated in Reference [31].

In the reference scenario, biomass makes 22% of the total primary fuel mix, whereas in the CEESA scenario it makes 100% of the fuel consumption. Since CEESA is a 100% RE scenario, biomass is the only primary fuel type that can be used. It is modelled to be refined through gasification, hydrogenation and fuel synthesis processes to meet other end-use fuel demands such as sea transport and aviation. The total fuel (biomass) consumption in the CEESA scenario is reduced to only 66 TWh, by large scale integration of fluctuating RE sources, compared to the 199 TWh in the reference scenario [31]. The biomass prices assumed are 5.6 €/GJ for both of the modelled systems in the analysis.

A discount rate of 3% is assumed for the socioeconomic calculation of annual investment costs. The CO_2 emission costs are assumed to be 15 €/ton [32]. This reflects the costs for societies generated by the CO_2 emissions. The cost level assumed here is in between the "low" and the "high" values found in the ExternE project [32].

Table 3
Results of the pipe network analysis for each of the analysed scenarios.

	Ref	S2	S3	S4
Heat demand [MWh]	8088	7888	7734	7617
Heat loss [MWh]	1365	1165	1010	893
Heat loss share [%]	16.87	14.77	13.06	11.73
Total pipe network investment costs [M€]	4.00	4.11	4.27	4.44

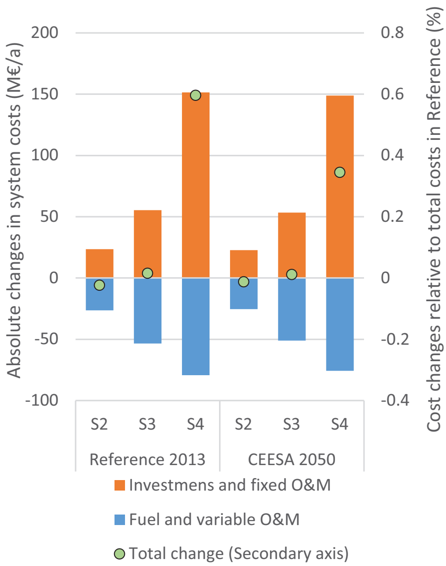

Fig. 9. Changes in total annual costs in the alternative scenarios, divided into variable and fixed costs and all scenarios related to the S1 scenario on the secondary axis.

5. Results

The results of the heat loss analysis model are presented in Table 3. It can be seen that the demands are decreasing from scenario S1 to S4 caused by the reduced heat losses whereas the costs are increasing.

The main results of the second part of the analysis are presented in Table 4. It can be seen that the changes in costs for S3 and S4 are positive which means that the total system costs have increased. The reductions in fuel consumption are present in all scenarios for both the reference and the CEESA 2050 system.

The S2 pipes have a marginal cost reduction and S3 pipes have a marginal cost increase at the assumed pipe costs, as seen in Fig. 9, whereas the S4 pipes will increase the total costs substantially. This means that in general it will be feasible to implement the S2 and S3 pipes since the costs increase is negligible and this scenario at the same time has a reduction in fuel consumption, as seen in Fig. 10.

Table 4
Results of the energy system analysis.

	Reference 2013				CEESA 2050			
	S1	S2	S3	S4	S1	S2	S3	S4
Total fuel consumption (TWh)	199.1	198.5	197.9	197.4	66.6	66.0	65.4	64.8
Relative change (%)	–	–0.30	–0.60	–0.88	–	–0.89	–1.82	–2.72
Annual system costs (B€)	90.4	90.4	90.4	91.0	158.5	158.5	158.6	159.1
Fuel and variable O&M	61.2	61.0	60.7	60.6	19.7	19.5	19.3	19.1
Investments and fixed annual O&M	29.3	29.4	29.7	30.4	138.9	139.0	139.3	140.0
Relative change (%)	–	–0.02	0.02	0.60	–	–0.01	0.01	0.35

Shows absolute values for fuel consumption in the system and total annual costs. The costs are divided into Fuel and variable O&M and Investments and fixed O&M. For both fuel consumption and costs, the relative change compared to the S1 scenarios is given.

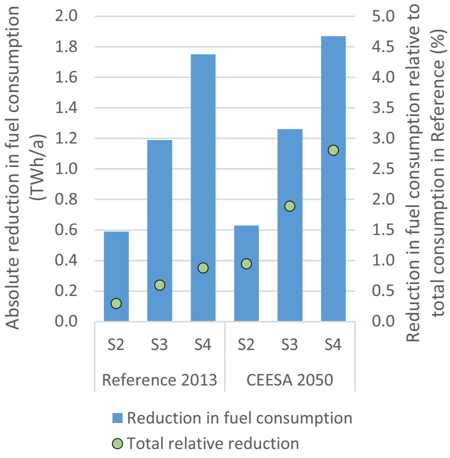

Fig. 10. Reductions in annual fuel consumption in the alternative scenarios.

6. Discussion

The presentation and demonstration of the methodology shows that this can provide valuable information for a short or long-term planning and decision making process and can qualify a discussion of the consequences of different alternative pipe insulation standards.

The methodology is designed for analysis of pipe insulation and heat losses, but can as well be applied for other similar issues where changes in DHNs or investments in the pipe system affect the heat losses. An example could be the choice of DH pipe types as suggested in Reference [12] or the design of pipe network layout suggested in Reference [33]. The strategy of reduced temperature level on the other hand, as suggested in Reference [9], is more complicated since the temperature level affects more parameters than included in this study, such as heat pump COP, electrical efficiency of thermal power production and the potential for integration of low-temperature heat sources. The effect of reduced supply temperature should therefore be analysed with a different methodology taking these into account.

7. Conclusion

The conclusion on the analysis indicates that S2 is socio-economically feasible today and that S3 is only about 1% in costs from being more feasible than S2 and at the same time more resource efficient, which points to S3 as the most feasible solution. From a pure cost perspective, the S4 is not attractive, even though it is the most fuel-efficient solution. It needs to be reduced 8–10% in price compared to S2 and S3. This scenario will mainly be relevant in the case of increasing scarcity of biomass fuel in the future, resulting in for example increased biomass prices or political restrictions on biomass consumption for energy production.

Acknowledgements

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PAPER 5

Socioeconomic Consequences of Short-Term Decisions on Large Heat Pumps and Biomass Consumption for Heat Strategies in Denmark

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Socioeconomic Consequences of Short-Term Decisions on Large Heat Pumps and Biomass Consumption for Heat Strategies in Denmark

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Abstract

The heat and electricity sectors in Denmark are currently undergoing a transition process. The existing stock of coal and gas fired combined heat and power plants in the country is old and a large share of this has recently been or will have to be decommissioned in the coming decade. With the Danish ambitions of 100% renewable energy in 2050, new coal-fired plants are not an option, so new alternatives that fit in the long-term strategy will need to be considered. Heat pumps in particular, are shown in a number of studies to have a large potential for integrating renewable energy into district heating, but only 25 MW_e is expected in the Danish Energy Agency's projection towards 2020.

The purpose of this study is to assess socioeconomic consequences of different technical alternatives on the short term for the heat and electricity sector in Denmark and recommend initiatives to support the most feasible development towards the long-term goal. Three alternative scenarios are analysed in the study, assuming heat pump capacities of 100-900 MW_e, and takes in account the development in district heating in Denmark. An analysis of the fuel and electricity market conditions are included as well to illustrate the sensitivity of the results to changes in the energy markets. The results show that there is a large potential for introduction of heat pumps in the Danish energy system with an approximate benefit of 20-90 M€/year and a saved fuel consumption of 4-8 TWh/year in the scenario with the highest heat pump capacities. This indicates that the economic framework for investment in heat pumps in district heating should be revised to strengthen the initiative to make investments in heat pumps rather than biomass boilers and combined heat and power with low electric efficiency.

Abbreviations

BAU	Business-As-Usual
CHP	Combined Heat and Power
DEA	Danish Energy Agency
DH	District Heating
HP	Heat Pump
IDA	Danish Society of Engineers
RES	Renewable Energy System
TSO	Transmission System Operator

1. Introduction

The political ambition for the Danish energy system is to have an energy supply independent of fossil fuels by 2050 [1]. The total primary energy supply in Denmark is in 2014 about 755 PJ. Out of this 660 PJ is fuel, including 137 PJ bio-energy. 48 PJ is wind and solar energy [2]. The potential for sustainable production of biomass in Denmark is only 240 PJ (67 TWh) [3] so the fossil fuels cannot just be directly replaced staying below this limit. This means that the energy demands should be reduced, energy efficiency increased or a combination of these. The consumption of especially wood pellets (in 2014, 37 PJ) for heat and power production has increased rapidly the last years, based on imported wood pellets. See Figure 1.

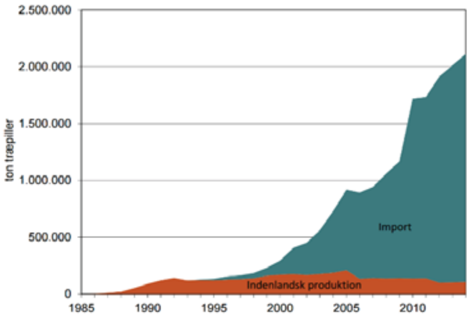

Figure 1 Development in domestic production (indenlandsk produktion) and import of wood pellets (træpiller) for Denmark from 1985 to 2014 [4].

The rapid increase is caused by a number of factors. Electricity prices have been historically low for several years and the cogeneration of heat and power is less feasible and at the same time biomass consumption is incentivised by very low taxes. This results in a development where new investments in district heating (DH) production capacity is mainly made in biomass boilers and biomass combined heat and power (CHP) with low electric efficiencies, which in general is making heat and power supply less energy efficient. A study has analysed different alternative CHP plant types for future energy systems, which indicates that the development towards more focus on production of heat rather than electricity is not feasible [5].

Heat pumps in DH is an option that potentially can increase the fuel efficiency by replacing direct fuel consumption in boilers with electricity combined with a surplus or waste heat source in a flexible manner. This enables e.g. wind and solar power to replace fuel consumption and increase energy efficiency. Currently, there is no substantial capacity of heat pumps in DH in Denmark. This is caused by the low taxes on biomass compared to electricity and a general restrain on long-term investments because of uncertainty about the future regulatory conditions for especially small CHP plants. The Danish Energy Agency expects a capacity of 25 MW_e of heat pumps in 2020 [2].

A number of studies have shown that heat pumps is an important part of an efficient energy supply system, not only on the short term, but also on the long term. In the IDA Energy Vision, scenario analyses show that heat pumps can play an important role in short term, as well as long term energy systems [6]. Similarly, in [7] it is argued that large heat pumps will be important in the development towards a 100% renewable energy system, to keep a high fuel efficiency and integrating renewable energy sources.

Several studies have shown that using electricity flexibly for DH production contributes with system flexibility, energy efficiency and reduction in system costs. Scholz and Müsgens analyse in [8] the increase in flexibility by introducing power-to-heat technology at CHP plants to improve integration of renewable energy sources (RES). It is concluded that "*the regulatory framework has a crucial influence on usage and profitability of a power-to-heat unit.*" In [9], Hagos et al. analyses heat pumps in DH to integrate RES. Through a scenario analysis it is shown that heat pumps can reduce the socioeconomic costs of the energy supply and in a system with biomass boilers heat pumps can help to limit biomass consumption. Blarke analyses different options for integration of wind power and concludes similarly in [10], that heat pumps in DH can reduce socioeconomic costs and compared to electric boilers as another power-to-heat technology, heat pumps are more cost-effective. An assessment of a potential 100% renewable energy system for Macedonia in [11], Ćosić et al. concludes that heat pumps in DH can contribute with energy efficiency and increase the penetration of intermittent RES in the energy system.

Two studies have as well analysed the potential of heat pumps in the context of the Danish energy system. In [12] Mathiesen and Lund analyses the potential for seven different technologies for integration of wind power in the Danish system and concludes that heat pumps have a potential in this context. Mathiesen et al. also concludes in [13] that heat pumps can play an important role in the Danish context in the short term future.

The present study analyses the socioeconomic consequences (excluding local externalities e.g. health benefits) of different alternative heating strategies towards 2020 for the case of Denmark. Here, the feasibility of heat pumps in DH systems is assessed given the existing and planned biomass-based heat production capacities as a prerequisite. Especially, there is a focus on the balance between replacement of biomass consumption for heating and investments in heat pumps and the socioeconomic consequences of choices in this connection, which has not previously been done.

2. Methods

The overall approach for the research is to compare different possible alternative scenarios for the DH supply in Denmark and the consequences of these. The scenarios are modelled and analysed in the EnergyPLAN energy systems analysis tool, which enables analysis of all energy sectors and the dynamic interrelations. A Business-as-usual (BAU) scenario is defined for the year 2020 to serve as a point of reference for the analysis of the alternative scenarios.

2.1. EnergyPLAN

EnergyPLAN is a scenario tool designed to model and analyse radical different energy systems, large-scale integration of renewable energy and the socioeconomic consequences of this. It is a deterministic input-output analysis tool, that is able to include all energy sectors (electricity, heating, cooling, transport and industry) and the tool calculates the dynamic interaction between the energy sectors on an hourly basis for one full year. This makes EnergyPLAN well suited for analysing the scenarios for this particular study. The tool is documented in [14].

In Figure 2 the general structure of EnergyPLAN can be seen. The tool works on an aggregated level, meaning that every individual plant is not modelled, but plants are grouped with other similar plants. For example, all thermal power plants are modelled as one, with a fuel mix and efficiency representing the average for the type of plant. The DH is divided into three different groups, to represent the differences, mainly in the relation to the electricity system. Fuel consumption is calculated based on the fuel mixes of the different plant types and the corresponding operation of these plants.

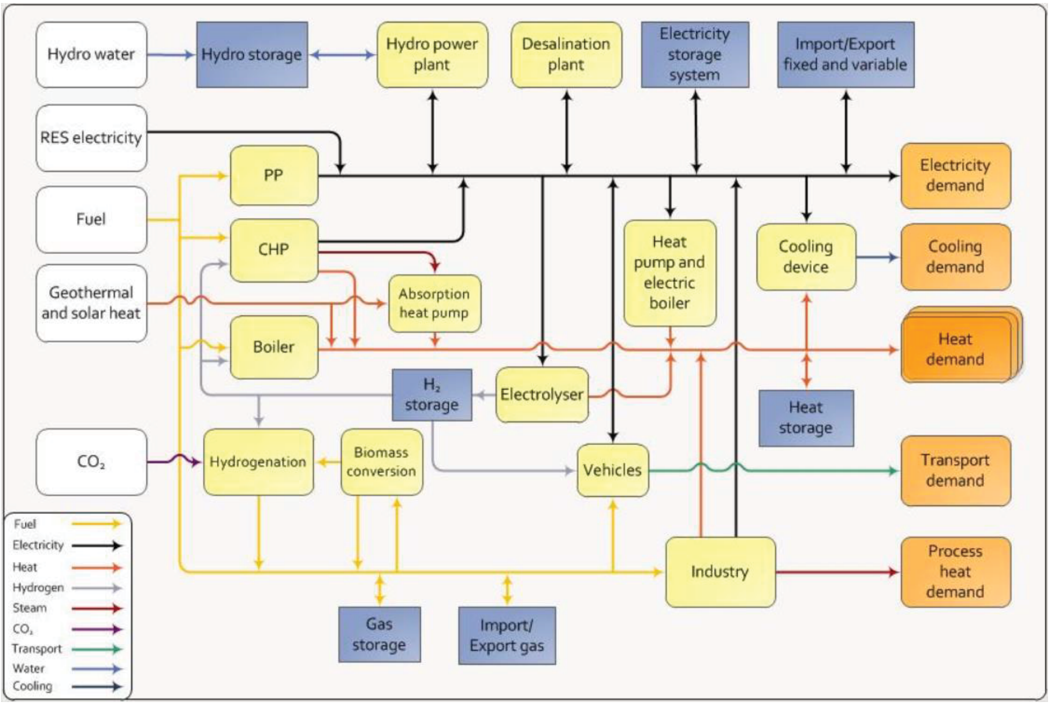

Figure 2 Conceptual diagram showing the main resources, conversion technologies, demands and connections between these in the EnergyPLAN tool [14].

The model is set to simulate the way the existing energy and electricity markets work, so that the units with lowest marginal production cost (including the external electricity market) produce the energy. The model takes into account the hourly dynamics between electricity and heat systems, for example a CHP unit can benefit from thermal storage capacity when producing electricity. The external electricity market is modelled as an hourly electricity price, a maximum transmission capacity and price elasticity in the electricity exchange.

In EnergyPLAN the socioeconomic costs are calculated as the sum of fuel and fuel handling costs, fixed and variable operation and maintenance costs, electricity import and export, annualised investment costs using a discount rate and CO_2-emmission costs. In this study a CO_2-emmission cost of 15.2 €/ton and a discount rate of 3% are used [15]. The costs for investments, fixed and variable operation and maintenance are from the DEA [16], except the investment cost for large-scale heat pumps, which is (3.43 M€/MW$_e$) from [13]. The assumed cost is higher than the cost from DEA (2.03 M€/MW$_e$) to avoid overestimation of the potential.

2.2. Definition of Business-As-Usual for 2020

The BAU scenario for Denmark in 2020 is the point of departure for the analyses. The scenario is defined according to the projection of the Danish Energy Agency for the Danish energy system in 2020. Most of the data needed for the model is available in the projection documentation [2,17]. In the following some key characteristics of the modelled energy system are listed:

Decentralised DH covers the DH systems where no large extraction CHP plants are located and likewise centralised DH cover DH systems where these *are* located.

- On- and offshore wind power production is equivalent to 54% of the electricity demand.
- District heating covers 56% of the total heating demand, of where 20% is in decentralised DH areas and 35% in centralised DH areas.
- CHP plants in centralised DH areas are operating on 75% biomass and 25% coal and natural gas whereas the decentralised ones operates on 63% natural gas and the rest operate on biomass.
- Fuel boilers in centralised areas are 90% driven on natural gas whereas decentralised boilers uses a mix of natural gas and biomass.
- Condensing power production is mainly based on coal consumption.
- Waste input for incineration is 10 TWh producing in total 5.4 TWh of DH and 2.4 TWh of electricity.
- Electric vehicles consumes 0.57 TWh, the capacity of heat pumps for DH is 25 MW_e and the solar thermal input is 0.9 TWh in decentralised DH areas.

2.2.1. Biomass CHP in Centralised DH Areas

In the centralised DH areas, biomass CHP is being developed in several places with the purpose of producing DH in a cheaper way, by shifting to less taxed fuel. Since the prices of electricity are low; biomass CHP plants with a focus on high DH output is being planned, e.g. at Amagerværket and Skærbækværket. This means that centralised CHP plants will be less dependent on electricity prices and more dependent on DH demands. To simulate this, a share of the CHP capacity in centralised DH areas (here, 240 MW_e and 675 MW_{th}) is changed into a fixed production capacity running base load in the heating season (May to September, approximately 6,000 hours of operation) and being closed in the summer (June to August).

2.2.2. Biomass Boilers in Decentralised DH Areas

Because of the tax reduction on biomass, plants based on more than 90% biomass boilers may not very likely invest in a heat pump before 2020, because the potential saving is small. Also, a number of DH plants using natural gas have gotten permission to install a biomass boiler to reduce production costs. It can also be seen as unlikely that this production will be replaced with a new heat pump investment. To avoid overestimating the potential of heat pumps, the heat demand as described above is moved to an independent DH group covered by only biomass boilers, where heat pumps are not introduced. The assumption that this demand is not available for heat pumps to replace, is tested in a sensitivity analysis in Section 3. In Figure 3 the mix of heat sources in all DH networks is shown, sorted according to heat sources, and showing the corresponding heat delivered to the networks.

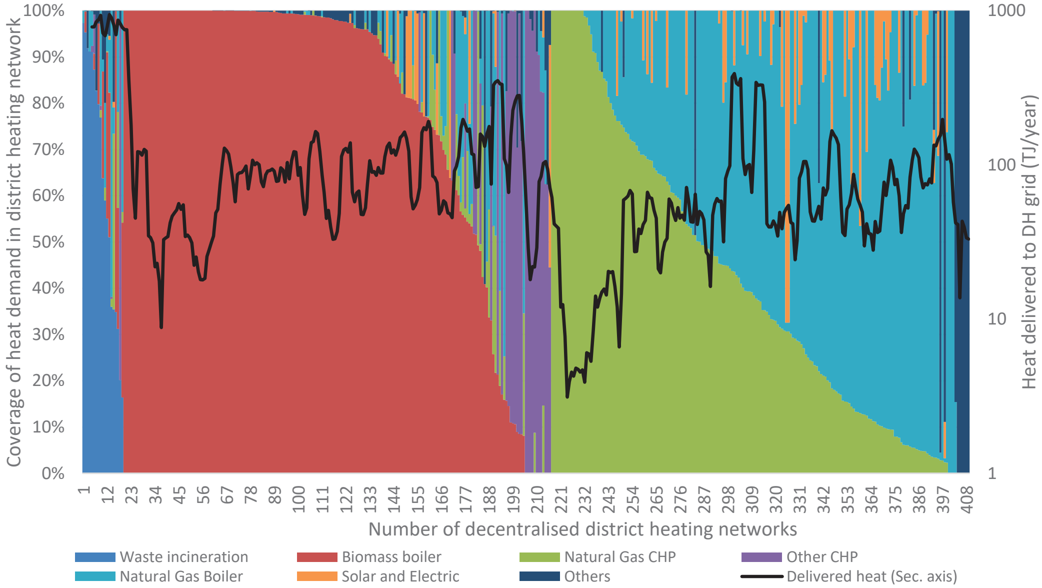

Figure 3 Diagram showing how decentralised DH plants cover their heat demands, sorted according to share covered by the different technologies. Delivered heat in each DH network is indicated by the black line (five-period average), referring to the secondary axis.

2.2.3. Electric Grid Stabilisation

The minimum electric grid stabilisation share is an important issue that needs to be discussed. In order to keep the grid stability, a constant frequency and voltage need to be maintained. When a sudden frequency drop occurs, the inertia of the system will try to follow the electrical load and return the grid frequency in balance. The inertia is linked mainly to the synchronous generators connected to the grid such as in centralised thermal power plants. However, the Danish Transmission System Operator (TSO) - Energinet.dk, has managed to run the system without any thermal power plant generation several times, meaning that the Danish energy system can be run without the synchronous generators. This requires that; capacity is available on the interconnectors with neighbouring countries, sufficient regulation bids are available in the Nordic region and that internal grid constraints are not met.

Although wind turbines do not provide electric inertia by nature, their inverters are fully controllable and thus, they are able to provide synthetic inertia if operated in that mode. This kind of operation can be used for a short term frequency support [18]. On the other hand, it should be kept in mind that the inverters have a very low overload possibility compared to the synchronous generators. In order for wind turbines to provide ancillary services such as up-regulation capacity, their power output should be purposely curtailed in order to be able to deliver additional capacity to the grid if needed. Variable speed wind turbine generators are able to provide power boost during the frequency decline [19]. The majority of new wind turbines in Denmark today are the ones with variable speed generators.

Considering the former discussion and examples of running the Danish power grid without any synchronous generators, the minimum grid stabilisation share of the synchronous generators is set to 10%, while 50% of wind power production is assumed to provide electric grid stabilisation.

2.3. Heat Pump Scenarios Analysed

The specific analyses performed in this study are described in this section. The analyses represent different strategies and conditions for the analysed system. The point of reference is the projection made by the DEA as presented in Section 2.2. Two main aspects are altered in the analyses; the capacity of heat pumps and the ability of heat pumps to replace biomass boilers.

The heat pump capacity is analysed at four levels as presented in Table 1. The heat pump capacity is divided between the decentralised and centralised DH areas to take into account the larger heating demand in centralised areas than the decentralised ones.

Table 1 Heat pump capacities for the alternative scenarios.

	Total (MW_e)	**Decentralised DH (MW_e)**	**Centralised DH (MW_e)**
Business-as-usual (BAU)	25	25	0
Conservative	100	50	50
Moderate	450	150	300
Extensive	900	300	600

In Section 2.2 it is described how and why a share of the DH demand is fixed to biomass boiler production. In a part of the analysis, this assumption is challenged and the heat pumps are able to replace all biomass boilers. The idea is that even though a given DH plant has invested in a biomass boiler, they might consider also investing in a heat pump. This can be done because biomass boilers have relatively cheap investment costs compared to the corresponding costs for fuel, and the investment might be paid back in few years. The naming of the two situations is defined as follows:

- **HP** Describes the stepwise introduction of heat pumps according to the four scenarios presented in Table 1 using the BAU assumptions (see Section 2.2) regarding biomass boilers.
- **HP Bio** Describes the same as **HP** but with heat pumps being able to replace all boiler production, including biomass boilers.

2.4. External Energy Market Analyses Assumptions

To assess the influence of the external energy markets, a sensitivity analysis of different price combinations is made of the main analysis results. Specifically, three different fuel price levels are assumed and five different electricity price levels. The energy market analysis method from the IDA Energy Vision [6] is applied in this study. The fuel price levels are based on [20] which estimates the crude oil price to be 131 US$/barrel in 2020, which defines the "High" price level, and is used in the BAU assumptions. The current level (2016) is used to define the "Low" price level. The two alternative price levels are defined by scaling the fuel prices according to the crude oil prices. See the applied prices in Table 2.

Table 2 Alternative fuel prices used in the energy market sensitivity analysis.

(€/GJ)	Coal	Fuel Oil	Diesel/ Gasoil	Petrol/ JP	Natural gas	Biomass	Dry biomass	Crude oil (US$/barrel)
Low	1.7	7.6	9.6	9.6	5.0	4.17	3.27	69
Medium	2.5	11.0	14.0	13.9	7.2	6.04	4.75	100
High	3.3	14.5	18.3	18.2	9.5	7.92	6.22	131

The applied electricity price levels are the same as in the IDA Energy Vision. Here, the five lowest price levels are used, because of the significantly shorter time horizon [6]. The applied average values are: 15, 31, 46, 62 and 77 €/MWh. The average value of 31 €/MWh is used in the BAU assumption.

3. Results

The results of the main analysis are presented in Table 3 and Table 4. Table 3 shows that increased heat pump capacity can significantly reduce the fuel consumption in the energy supply. Exchange of electricity can have a significant influence on the results of fuel consumption. Therefore it is tested which effect this has, by removing the ability to import and export electricity, and the results are very similar for both cases. It can also be seen in the table that HP Bio situation shows a better potential for heat pumps than the HP situation, which is caused by the improved ability to replace biomass boilers.

It is important to note that the saving relative to the absolute values are low, because these include the whole energy system including individual heating, industrial fuel consumption and transport, which are not influenced by heat pumps in district heating in this model. To put it on a scale; the fuel consumption in the BAU 2020 is 200 TWh/year, but only about 50 TWh/year is consumed in CHP production, fuel boilers for DH or condensing power production, which are influenced by large heat pumps.

Table 3 Fuel consumption and savings from the main analysis for the different scenarios.

(TWh/year)	**HP**		**HP Bio**	
	Fuel consumption	Saving	Fuel consumption	Saving
BAU 2020	200	-	200	-
Conservative	199	1.0	199	1.1
Moderate	196	5.0	195	5.6
Extensive	194	6.5	192	8.0

Table 4 shows that increased heat pump capacity can also reduce the socioeconomic costs of the energy supply. All the three alternatives to the BAU can reduce the total costs. The extensive expansion of heat pump capacity can reduce the costs, but not more than the moderate expansion. It can also be seen that the savings are on the same level in the HP Bio situation as in the HP, which is different to the results for the fuel consumption.

Table 4 Socioeconomic costs and savings from the main analysis for the different scenarios.

(M€/year)	HP				HP Bio			
	Total costs	Investment cost	Fuel cost	Total saving	Total costs	Investment cost	Fuel cost	Total saving
BAU 2020	12,320	2,420	8,340	-	12,330	2,420	8,360	-
Conservative	12,300	2,440	8,290	30	12,310	2,440	8,310	20
Moderate	12,240	2,520	8,100	80	12,250	2,510	8,110	90
Extensive	12,250	2,620	7,940	80	12,250	2,620	7,950	80

The results of the sensitivity analyses are shown in Figure 4 and Figure 5. The figures show the analysis where the BAU scenario is compared to the HP (Moderate) scenario. In Figure 4 it can be seen that the HP scenario has lower fuel consumption for all of the analysed combinations of fuel and electricity prices. It can also be seen that the general fuel consumption is increasing and the saving in fuel consumption is decreasing with higher electricity prices. This is caused by the heat pumps operating less and therefore replacing less boiler production. For the reference electricity price level of 31 €/MWh, it can be seen that the saving in fuel is ranging from 5 TWh/year assuming high fuel prices, but even at low fuel prices this is only reduced to 4 TWh/year.

In Figure 5 it can be seen that at Medium and High fuel costs the HP scenario has lower socioeconomic costs than the BAU in all price combinations. In the case of Low fuel prices and electricity prices above 46 €/MWh, the BAU scenario has slightly lower costs. This means that if fuel prices decrease and electricity prices increase, the economic feasibility of heat pumps is decreasing, but this is not seen as a likely development.

4. Discussion and Conclusion

The results show that implementation of large heat pumps in district heating in Denmark towards 2020 is improving both the fuel and cost efficiency of the energy supply, taking into account the existing biomass boiler and CHP capacities. Increased capacity of heat pumps can replace large shares of the heat-only production on fuel boiler. There is a potential of saving 4-8 TWh of fuel per year and 20-90 M€/year if heat pumps are introduced into district heating systems.

At DH plants where biomass boilers are the only heat source or a central part of the production, heat pumps might also be able to reduce costs by replacing the fuel consumption of the boiler. This means that fuel consumption can be reduced without increasing costs, which will save biomass resources for other purposes in the energy system, and make a future transition of the transport sector cheaper and more sustainable.

The energy market analysis shows that heat pumps will be a benefit in the majority of potential market conditions, except if the electricity price / fuel price ratio increases significantly. This means that the investment in large heat pumps in district heating is not a big risk. In the best and most likely cases, heat pumps will make the energy supply more cost and fuel-efficient. In the worst case it will still make the system more fuel efficient, but slightly less cost effective than the BAU.

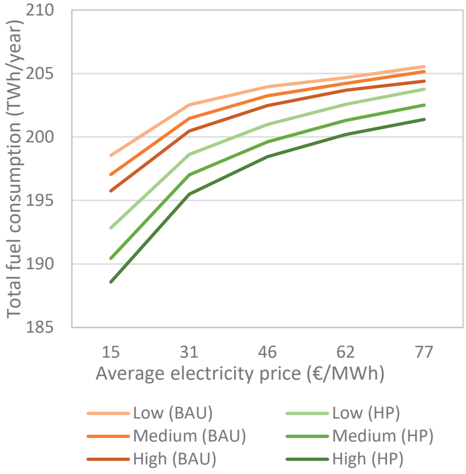

Figure 4 Energy market sensitivity analysis of fuel consumption. Low, Medium and High refer to the fuel price levels. BAU is the Business-as-usual scenario and HP shows implementation of 450 MW_e of heat pump capacity (Moderate scenario).

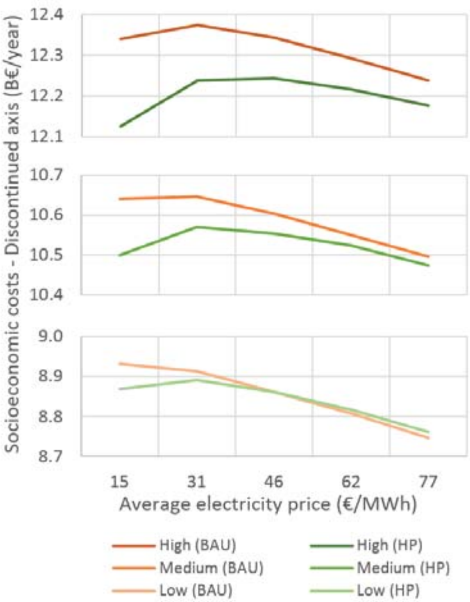

Figure 5 Energy market sensitivity analysis of socioeconomic costs. Low, Medium and High refer to the fuel price levels. BAU is the Business-as-usual scenario and HP shows implementation of 450 MW_e heat pump capacity (Moderate scenario).

In the countries Sweden, Norway and Finland with similar DH system development and heat demand patterns [21], there are already capacities of scale heat pumps for DH production, in the scale of 10 MW and above per plant. In [22] examples from all the three countries are described, using waste water, sea water and air as heat sources. This also indicates that large-scale heat pumps can be a feasible solution in Denmark.

On the basis of the results of this study it can be recommended to revise the regulatory framework related to heat pumps in district heating, since the socioeconomic potential will not be achieved assuming the current projected capacities.

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PAPER 6

Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective

International Journal of Sustainable Energy Planning and Management (In review)

6

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Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective

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ABSTRACT

District heating (DH) systems are important components in an energy efficient heat supply. With increasing amounts of renewable energy, the foundation for DH is changing and the approach to its planning will have to change. Reduced temperatures of DH are proposed as a solution to adapt it to future renewable energy systems. This study compares three alternative concepts for DH temperature level: Low temperature (55/25 °C), Ultra-low temperature with electric boosting (45/25 °C), and Ultra-low temperature with heat pump boosting (35/20 °C) taking into account the grid losses, production efficiencies and building requirements. The scenarios are modelled and analysed in the analysis tool EnergyPLAN and compared on primary energy supply and socioeconomic costs. The results show that the low temperature solution (55/25°C) has the lowest costs, reducing the total costs by about 100 M€/year in 2050.

Keywords:

Energy system analysis;
Socioeconomic costs;
Fuel consumption;
Energy efficiency;
EnergyPLAN simulations;

URL:
dx.doi.org/10.5278/ijsepm.2017.12.2

Abbreviations:

COP	Coefficient of performance
DEA	Danish Energy Agency
DH	District heating
DHW	Domestic hot water
HP(s)	Heat pump(s)
IDA	The Danish Society of Engineers
LTDH	Low-temperature district heating
PES	Primary Energy Supply
RE	Renewable energy
SH	Space heating

1. Introduction

Existing district heating (DH) systems and organisations are challenged by the transition towards 100% renewable energy (RE) supply [1]. The RE sources are variable in time which is different from the conventional heat supply based on fossil fuels that can be combusted according to the demand. This is not only the case for DH, but for all energy sectors (electricity, transport, industry etc.), and a holistic approach including all sectors is needed to develop an efficient energy supply in the context of 100% RE [2].

At the same time heat savings are implemented in the building stock and new buildings are of much better energy standards that the old ones, which will reduce the heat demand density and thereby further challenge the existing DH supply. Also the economic framework for DH

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production will change, as RE to a larger extent is based on investment costs rather than fuel consumption [3].

The 4th generation of DH (4DH) is a framework in which solutions for these challenges can be developed. 4DH emphasises the need to integrate DH more with other energy sectors, by introducing new heat sources and conversion technologies that utilise synergies between the sectors. It is also a key element that the temperature levels of DH supply generally should be reduced to improve production efficiencies and reduce grid losses [1].

1.1. Low-temperature district heating

A number of studies have investigated the concept of low-temperature district heating (LTDH) and aspects of this including benefits, challenges, costs and possible future technological solutions.

In [4] Dalla Rosa et al. model a DH system in Canada in detail comparing different temperature sets, concluding that supply temperatures reduced towards 70 °C from above 100 °C is a feasible solution, whereas lower temperature sets (below 60 °C) depend on the achievable system benefits because of increased costs. Similar tendencies are found by Ommen et al. [5] for the heat and electricity systems of Greater Copenhagen. Here, supply temperatures below a level where electric boosting of domestic hot water (DHW) become necessary, are found not to be feasible in terms of consumer costs.

Baldvinsson and Nakata compare in [6] medium temperature DH with LTDH, LTDH with low heat demand and a combination of medium temperature DH and LTDH in a cascading system, for a specific mixed urban area in Japan. It is found that in a system with normal heat demand LTDH is not feasible, compared to LTDH combined with low heat demand which is feasible. For the latter, the optimal plant supply temperature level is found to be around 52 °C in general with temperature boosting up to 65 °C in the winter. In another study on LTDH for some very different case areas in Austria, the energy, economy and ecology are assessed for scenarios with different temperature configurations, some with electric DHW temperature boosting and some without [7]. The results show to be different for the different cases, but generally conclude that the availability of low temperature heat sources to the DH system is important.

Among the challenges of implementing LTDH is the need for reduced return temperature to maintain a good temperature difference between supply and return. Gadd and Werner present in [8] a method for fault detection in DH substations to avoid high return temperature using the temperature difference as indicator. If the return temperature cannot be sufficiently reduced, the pipe dimensions or pumping costs will increase to cover the same heating demand. Tol and Svendsen describe in [9] a method to dimension the pipe system in LTDH systems in an optimal way introducing temperature boosting in peak demand times, and thereby keeping pipe dimensions and heat losses to a minimum.

Another challenge is the sufficiency of the supply temperature to meet heat demands in the buildings. Østergaard and Svendsen indicate in [10], based on simulation of typical building types, that it is feasible to provide space heating (SH) to even old buildings, that have been energy refurbished, using DH supply temperatures below 50 °C. The DHW is more complicated because of the risk of legionella infection. Yang et al. present in [11] a number of solutions for prevention of legionella infection in the DHW supply. These include temperature boosting using electricity, limitation of DHW volume using instantaneous heat exchangers and different sterilization methods. Furthermore, Yang et al. [12] assess different DHW preparation methods for supply temperatures below 45 °C using direct electric heating or HP boosting to a sufficient temperature level. Østergaard and Andersen [13] even consider a supply temperature as low as around 35 °C, using a booster HP, which is also indicated on the basis of the demonstration project in [14]. Electricity consumption for heating is generally not an efficient solution in a system perspective [15] which is also found in [16], but might provide a new picture when combined with temperature reductions in DH.

No studies have so far analysed the temperature level on a large scale energy system level from a societal point of view, which is necessary to provide more general recommendations.

1.2. Long-term energy system analysis

In this study five scenarios describing five concepts of DH with a focus on different temperature levels are chosen and the costs and benefits of each of these are assessed. The study will have its point of departure in a Danish context analysing the scenarios implemented into holistic energy models of Denmark for 2035 and 2050 developed in the IDA Energy Vision project where scenarios from the Danish Energy Agency (DEA) are used as reference. Here, the "Wind" scenario is most similar to the IDA scenario [17]. This study indicates, by socioeconomy and fuel consumption, which DH concept generally fits best

Table 1: Main characteristics of considered concepts for district heating in future energy systems

	Conventional	Low Return Temp.	Low Temp.	Ultra-Low Temp. (Elec.)	Ultra-Low Temp. (HP)
Nominal supply temperature [°C]	80	80	55	45	35
Nominal return temperature [°C]	40	25	25	25	20
Additional DHW preparation method	–	–	–	Direct electric	Booster heat pump

into a future RE system in Denmark, and thereby contributes to how DH can be seen in the overall strategy and planning for the Danish energy sector.

For this study, a number of concepts within LTDH is identified on characteristics of the temperature set and means for DHW preparation with a conventional temperature set as reference. These are presented in Table 1. These concepts are further defined and put into an energy system context in Chapter 2.

In this paper the analysis and results are presented in the three following chapters. In Chapter 1 an introduction, literature review and background for the area is presented. In Chapter 2 the materials and methods are presented, first describing the purposes of the different scenarios followed by details on the assumed differences between the scenarios. The results of the analyses are presented in Chapter 3 and in Chapter 4 results and the implications of these are discussed comparing them with previous findings.

2. Materials and methods

The scenarios, characterising different DH concepts, use existing models of the energy system in Denmark for 2035 and 2050, implementing changes in these consequent to the change of temperature assumption. The changes include grid losses, energy production and conversion efficiencies, potential utilisation of heat sources and investment costs in buildings and the supply system.

2.1. Analysed scenarios

The analysed scenarios are based on the scenarios designed in the project IDA Energy Vision [17] for 2035 and 2050. These scenarios assume some degree of reduced temperature in the DH systems, but no specific temperatures are mentioned. Here, it is assumed that the IDA scenarios are equivalent to the Low temperature scenario (55/25) of the present study, and the dependent parameters are calculated for the other scenarios based on this. The analysed scenarios can be seen as a stepwise progression in reduction of temperatures and interventions in the buildings. They are briefly described below:

- **Heat savings** (Save) serves as a reference for the other scenarios and represents a situation where savings in space heating have been implemented (as for all the five scenarios) but the DH temperatures are kept at a conventional level. This is done because savings in heat demand is a prerequisite for reducing the temperatures in a feasible way.
- **Low return temperature** (Return) represents a situation where implementation of building improvements to reduce the return temperature is performed while keeping the conventional supply temperature. The purpose of the scenario is to show the relevance of reducing the return temperature.
- **Low temperature** (Low) represents a situation where both supply and return temperatures are reduced to the lowest possible level where no electric boosting of DHW in the buildings is necessary.
- **Ultra-low temperature using direct electric boosting** (Ultra) represents a situation where the supply temperature is further reduced, making temperature boosting of the DHW necessary, here done using direct electric heaters.
- **Ultra-low temperature using heat pump boosting** (HP) represents a situation where the supply and return temperatures are further reduced, here using micro HPs to boost the DHW temperature as needed. This scenario is based on more assumptions and simulated data compared to the others for which better data is available.

2.1.1. Domestic hot water preparation

In the three first scenarios it is assumed that the preparation of DHW is solely done with an instantaneous heat exchanger, whereas in the scenarios Ultra and HP, electric boosting is needed to provide a comfortable DHW supply limiting the risk for legionella. All scenarios are designed to be able to meet the same comfort and hygienic requirements [12].

In the Ultra scenario electricity is consumed in an electric heater in the DHW system of the building. Here, the water is heated according to the official comfort requirements of 45°C, after preheat by DH. The hygienic requirements, to avoid legionella are not compromised in this way because the water is heated instantaneously. In cases with long internal pipe systems it may be needed to use electric tracing [18]. The electricity consumption is assumed to be 14% of the DHW demand [12], and since this electricity is heating the DHW it is assumed to replace an equivalent amount of the heat supply from DH.

In the HP scenario the electricity consumption is for the compressor in the HP. The heat pump is placed in a separate circuit with a storage tank and a heat exchanger connected to cold usage water. The water is stored at 50°C to be able to meet comfort requirements after the heat exchanger. This is done to reduce the needed capacity of the booster heat pump and the frequency of on/off switches. Here, as well, the hygienic requirements are not compromised because the DHW is produced instantaneously on demand. The temperature has to be raised more than in the Ultra scenario because of the lower supply temperature and storage requirement, but because of the COP of the HP the electricity consumption is at the same level. It is here assumed to be 16% of the DHW demand, based on data from [13] provided by the authors, in which the used booster HPs are presented and discussed. The COP of these varies from 5.5 to 7.5 during the year.

The electricity demands in the Ultra and HP scenarios are distributed according to the variations in DHW demand. In the HP scenario, where individual thermal storages are integrated, it may be possible to use the HPs intelligently, but compared to the household HPs for heating, these booster HPs are small in capacity and the effect will be small [19].

2.1.2. Additional costs

When comparing the scenarios, a number of cost assumption related to the differences in the scenarios are made. The three categories and the specific cost assumptions made can be seen in Table 2.

To reduce the return temperature from the majority of buildings, some replacements of valves and radiators will be required, which is estimated in [20] to be approximately 10,000 DKK (1,300€) per building. For the calculation of the total additional costs it is assumed that the replacement of valves and radiators will be done on average 10% before the end of their technical lifetime or have equally higher investment costs than standard devices.

The electric heater is today available in retail, but as an independent unit supplementary to the DH substation. The model used in [12] can be purchased for approximately 900€ [21]. If the Ultra scenario is implemented in a larger scale, it can be assumed that the unit will be sold in larger numbers and be an integrated part of the DH substation, reducing the costs. It is here assumed that the unit cost can be reduced to 220€ (one third of the cost for the micro HP).

The micro booster HP is not available today in retail, but the units have been developed for a demonstration project in single family houses, where the additional cost for the HP unit is 15,000 DKK (2,000€) [14]. The HP is here an integrated part of a DH substation, but it is assumed that the cost can be reduced to 670€ (one third of the demonstration unit cost) accounting for the potential benefit in multifamily buildings and the economy of scale in the production of larger quantities. The sensitivity of the results to these assumptions are discussed in Section 4.3.

Table 2: Assumptions on additional costs for the different scenarios

Category	Parameter	Save	Return	Low	Ultra	HP
1. Valves and radiators	Replacement [€/building]	0	130	130	130	130
	Total annualised cost [M€/year]	0	19	19	19	19
2. DHW heater /	Investment [€/building]	–	–	–	220	670
micro booster HP	Total annualised cost [M€/year]	–	–	–	37	112
3. DH grid costs	Total DH grid costs [B€]	20.1	20.0	20.3	20.5	20.7
	Change in grid costs [%]	–1.0	–1.5	–	1.0	2.0
	Total annualised cost [M€/year]	869	865	878	887	896

The different scenarios have different average temperature differences between supply and return, which means that a different flow rate is required to deliver the same amount of heat. On the short term, this will mean different flow and cost for pumping, but on the long term it is assumed that these changes will be evened out by using more appropriate pipe dimensions. This is also indicated in [7] and [4]. It is in general assumed that the DH grid is replaced gradually and the differences in costs will therefore only be related to the dimensions of the pipe networks, because the replacement will be done at some point anyway. Therefore, based on the relative changes in temperature difference, the total pipe costs are assumed to change according to the rates seen in Table 2. The total DH grid costs are estimated based on the method presented in [22]. It is assumed that the insulation standard in 2035 is an average of Series 2 and 3 whereas in 2050 it assumed to be an average of Series 3 and 4 due to gradual improvement of pipe insulation standard towards 2050.

The values of total annualised costs in Table 2 are calculated based on the total investment cost, the technical lifetime of investments and a discount rate (See Section 2.3). Valves, radiators, electric heater and micro HPs are assumed to have technical lifetimes of 20 years, whereas the DH grid is assumed to have a technical life time of 40 years [23].

2.2. The EnergyPLAN analysis tool

EnergyPLAN is an advanced energy system analysis tool developed for analysis of large scale energy system dynamics which allows for modelling of 100% RE. It is a simulation tool that calculates one full year on an hourly time resolution. Special focus is on the integration of the different energy sectors: electricity, heating, transport, and industry and the dynamics between these on an hourly basis. EnergyPLAN has also been applied in [3], [17], [22] and [24] for modelling of 100% RE systems. A complete documentation of this can be found in [25].

For this analysis, a modified version of EnergyPLAN has been developed where version 12.4 has been used as a starting point. The modification changes the input type of the COP for HPs in DH from a fixed value to an hourly time-dependent input. This is done to reflect the changes in COP when the supply and return temperatures and the temperature of the heat source are changed.

2.3. Socioeconomic cost calculation

The socioeconomic costs are calculated as total annual costs for the given energy system including annualised investments costs, fuel costs, variable and fixed operation and maintenance costs and CO_2-emission costs. The investments are annualised using a discount rate of 3%. Public economic measurements as taxes, levies, subsidies etc. are not included in the socioeconomic costs.

2.4. Application of temperature profiles

The temperature levels of DH systems are not constant from hour to hour or month to month, e.g. due to compensation for demand fluctuation. These changes may have an influence on the system benefits of low temperature DH. Therefore, parameters sensitive to DH temperature changes have been calculated with an hourly time resolution based on temperature profiles.

Temperature measurements from the Danish Rindum DH plant from 2015, provided by the plant manager, have been used to calculate temperature profiles for Heat Savings, Low Return, Low temperature and Ultra-low temperature scenarios. For the HP scenario, simulated data from [13] have been used to calculate the hourly profiles.

Table 3 shows the assumed average temperature levels in the DH systems for the high heating season (November-April), and low heating season (May-October). The temperatures are not calculated dynamically, but the measured profiles are scaled to meet the level seen in the table. This means that the return temperatures are not depending on the supply temperatures.

Table 3: Average temperature levels in the scenarios for the highand low heating seasons

[°C]	Save.	Return	Low	Ultra	HP
Supply temperature – heating season	80	80	58	45	35
Return temperature – heating season	40	25	25	25	20
Supply temperature – low heating season	73	73	54	41	30
Return temperature – low heating season	42	26	26	26	18

The resulting temperature profiles are shown in Figure 1 and Figure 2 shows the profile of the 20 °C return temperature has a different tendency than the two others. This is caused by the ability of the booster HP in this scenario to decrease the return temperature in the non-heating season further than the output of the SH system.

The temperature profiles have been used to calculate hourly heat losses, COP of HPs and efficiency of solar thermal production. The details of how the temperatures have been applied to calculate these inputs are described further in Sections 2.5 and 2.6.

2.5. District heating demands and losses

The heat demand in DH describes the total demand for heat input to the buildings supplied with DH. This includes SH, DHW and internal heat losses from the HPs in the HP Scenario. The heat demands for the scenarios are calculated based on the figures presented in the *Future Green Buildings* project [26] for the building stock and potential heat savings. It is assumed that 66% of the total heat demand will be covered by DH in 2035 and 2050. Here the total savings in SH in existing buildings are 45% towards 2050. The demand

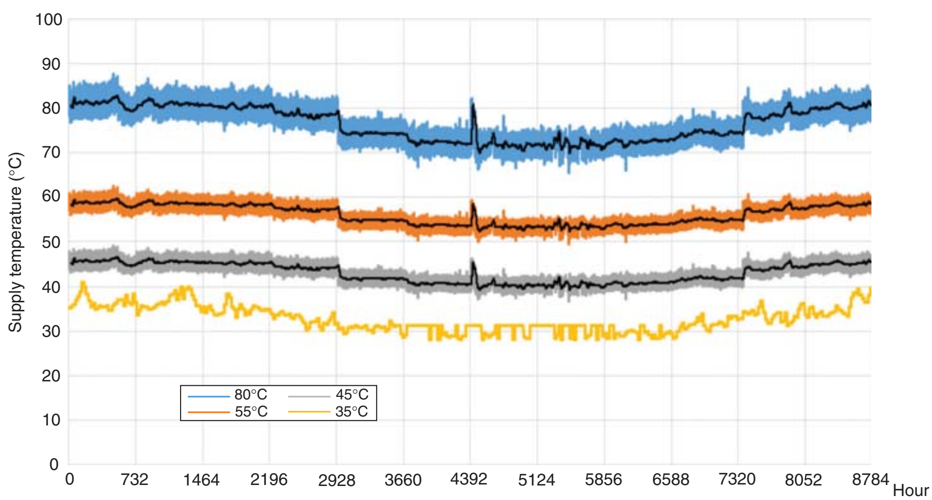

Figure 1: Hourly supply temperature profiles applied in the analyses. For 80, 55 and 45 °C a 24-hour moving average is added (black lines) to show the general trends

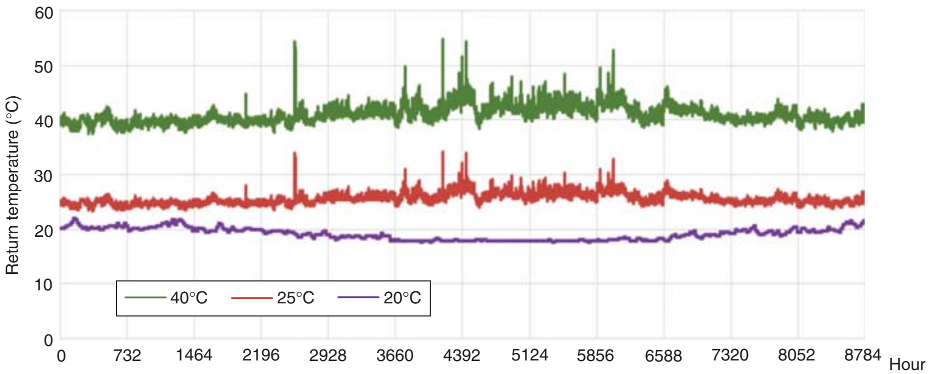

Figure 2: Hourly return temperature profiles applied in the analyses

Table 4: District heating demand and production composition for the scenarios in 2035 and 2050

[TWh]	2035 Save	2035 Ret	2035 Low	2035 Ultra	2035 HP	2050 Save	2050 Ret	2050 Low	2050 Ultra	2050 HP
Space heating	21.4	21.4	21.4	21.4	21.4	18.4	18.4	18.4	18.4	18.4
Domestic hot water	3.8	3.8	3.8	3.8	3.8	4.3	4.3	4.3	4.3	4.3
Heat from electricity	–	–	–	–0.5	–	–	–	–	–0.6	–
Thermal storage loss	–	–	–	–	0.4	–	–	–	–	0.4
HP heat loss	–	–	–	–	(0.3)	–	–	–	–	(0.3)
Internally utilised loss	–	–	–	–	–0.2	–	–	–	–	–0.2
Total demand	25.2	25.2	25.2	24.7	25.4	22.7	22.7	22.7	22.1	22.8
Total grid loss	5.0	4.7	4.2	3.8	3.6	3.9	3.7	3.2	2.9	2.7
Grid loss / production [%]	16.5	15.8	14.1	13.2	12.3	14.7	14.1	12.4	11.4	10.5
Total production	30.2	29.9	29.4	28.4	28.9	26.5	26.3	25.8	24.9	25.5

in new buildings are 41.3 kWh/m^2 for SH and 13.7 kWh/m^2 for DHW.

In Table 4 the components of the heat demands are presented. SH and DHW are fixed through all five scenarios, but different between 2035 and 2050 because of continued implementation of heat savings and a general change in the building stock and use. Based on [12] it is assumed that 14% of the DHW demand in the Ultra scenario is covered by electricity. For the HP scenario it is assumed that it has a thermal storage [13,14] with a heat loss of 10% of the DHW. 50% of the electricity consumption in the pump (16% of the DHW based on data from [13]) is considered a loss that can be utilised for SH, corresponding to 50% utilisation of the electricity for the thermodynamic cycle. This is not counted in the total demand because it is from electricity and therefore in brackets in the table. For the heat losses from thermal storage and electricity consumption in the HPs, it is assumed that 30% can be utilised in the building as SH and the rest is lost as increased heat loss from the building, due to location of the HP and operation during low heating season.

The grid losses are calculate based on results from modelling and analysing the flows in a DH network using the DHM-model applying different pipe insulation series and DH temperature levels [27], [22]. The grid loss (See Table 4) is distributed to an hourly profile using the supply and return temperatures at plant level.

2.6. Efficiency of energy conversion units

Most energy conversion units in DH systems depend on the supply and/or return temperatures in the network. In the following, the included production units whose efficiency are affected by the DH temperatures are presented and it is explained how their relation to the DH temperatures is included in the analysis.

2.6.1. Condensing boilers

Fuel boilers in DH can improve their efficiency by condensing the flue gas from the combustion. The lower the return temperature received from the grid, the more heat can be extracted from the flue gas. How much the efficiency can be improved depends on the fuel type and moisture content. Based on [28] it is assumed that reduced return temperature from 40 °C to 25 °C and 20 °C will improve the average efficiency of fuel boilers from 0.95 to 1.00 and 1.02 respectively.

2.6.2. CHP plants

CHP plants mainly benefit from a reduction in the supply temperature. As the supply temperature from a CHP plant is lower, the electric efficiency will improve because of a higher total temperature difference. A Carnot efficiency equation has been used. See Equation 1.

$$\eta = 1 - \frac{T_{Low}}{T_{High}} \tag{1}$$

Here, η is the Carnot efficiency, T_{Low} [K] is the supply temperature and T_{High} [K] is the high temperature in the combustion [29]. T_{High} is here assumed to be 500 °C. The found efficiencies are used to scale the CHP electric efficiencies from the IDA models. The thermal efficiencies of the CHP are reduced corresponding to the increase of the electric efficiency to keep the same overall efficiency.

2.6.3. Heat pumps

The coefficient of performance (COP) of a HP improves with both supply and return temperature reductions. The calculation of the HP COP is based on a Lorenz cycle. See Equation 2.

$$COP = \eta * \frac{T_{High}}{T_{High} - T_{Low}} \tag{2}$$

Here, η is the system efficiency of the HP, assumed to be 0.4 (including losses in heat exchangers between HP refrigerant and DH and heat source fluid), T_{High} is the logarithmic mean high temperature in the direct and T_{Low} is the logarithmic mean low temperature of the HP evaporator [13,30]. T_{High} and T_{Low} are defined in Equation 3.

$$T_{High} \; or \; T_{Low} = \frac{T_{in} - T_{out}}{Ln(T_{in}) - Ln(T_{out})} \tag{3}$$

Here, T_{in} and T_{out} are the inlet and outlet temperatures of the condenser and the evaporator in the HP. It is assumed that the heat source for the HPs can be cooled 5K.

The COP is calculated for every hour, based on the DH temperature profiles described in Section 2.2 and a heat source profile. The heat source temperature (See Equation 4), should resemble an average of all the utilised heat sources. The seasonal variations are defined by measurements of sea water temperatures from [31]. Other heat sources, such as low-temperature industrial waste heat or sewage water, often have higher temperatures than sea water. Therefore, a constant temperature addition ($K_{Addition}$) is added to the sea water temperature ($T_{Seawater}$) to calculate an estimate heat source temperature ($T_{Heat\ source}$).

$$T_{Heat\ source} = T_{Sea\ water} + K_{Addition} \tag{4}$$

The constant temperature addition ($K_{Addition}$) is different for central DH in the bigger cities compared to the decentral DH in the smaller towns. In the bigger cities, the amount of good heat sources relative to the heat demandis lower than in the smaller towns [32]. The better heat sources with higher temperatures are assumed to be utilised before those with lower temperatures. At some point, a DH company will run out of good heat sources, and they will have to use less efficient heat sources to further expand the heat pump capacity. This point will occur earlier in the bigger cities (central DH) than in the small towns (decentral DH) because of the lower amount of heat sources per demand. This is taken into account by defining $K_{Addition}$ to 10K for the decentral DH, but only 5K in the central DH.

2.6.4. Solar thermal

The output of solar thermal plants depends on the supply and return temperatures but also the ambient temperature of the solar thermal panels. The bigger the temperature difference between the temperature of the working fluid in the solar panel and the surrounding air, the larger the heat loss and thereby lower efficiency [33]. The relation is shown in Figure 3.

2.6.5. Geothermal

In the Danish context, geothermal resources are only utilised for DH in three locations, and all using absorption HPs. The benefits of lower DH temperatures to the production from geothermal plants are mentioned in several studies, including [1,35]. No quantitative assessment of the potential has been found, though. Here, it has been assumed that a reduced return temperature improves the annual production, as the temperature difference thereby increases by 5% and 7% when reduced to 25°C and 20°C respectively. Reduced supply temperature is assumed to reduce the need for HPs and thereby the costs for geothermal plants. The HP accounts for 29% of a geothermal plant costs [36], and it is assumed that 50%, 75% and 100% of this can be

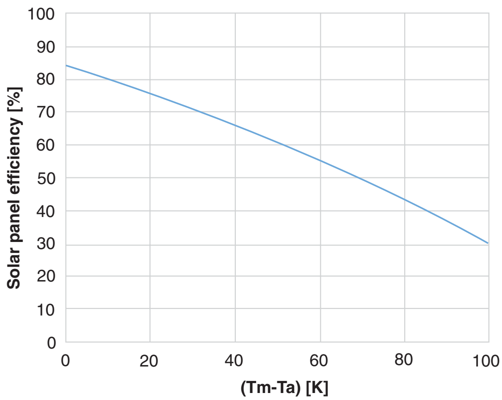

Figure 3: Efficiency of a solar panel as a function of the temperature difference between the medium panel temperature (Tm) and the ambient air temperature (Ta). Derived from [34]

saved at 55 °C, 45 °C and 35 °C respectively. This is assuming that the geothermal heat source is above 35 °C, which is the case for all plants in Denmark [37].

2.6.6. Industrial excess heat

Excess heat from industrial processes can be used for DH supply either using HPs or via direct heat exchange. Direct heat exchange requires the DH supply temperature to be lower than the one for the excess heat. In [38] it has been assessed that 4 PJ of low temperature excess heat can be recovered using HP at today's temperature sets. Following this, it is in this study assumed that 25%, 50% and 75% of this can be recovered for DH supply in direct heat exchange, as the supply temperature is reduced to 55 °C, 45 °C and 35 °C respectively.

2.7. Required production capacity

An indirect effect of improved efficiencies and reduced demand in the DH system is the change in the required production capacity, due to changes in peak demand and utilisation time of the conversion units. This is done to include the potential change in investment costs related to production facilities and thereby making the scenarios economically comparable. The changes are performed iteratively to make all parameters match the requirements in the results of the final simulation. The following list presents all capacities that have been updated and how these have been updated.

- **Fuel boilers** in DH systems have been adjusted in capacity relative to the change in peak heat demand.
- **Condensing power plants** have been adjusted relative to peak electricity demand. This is only relevant in the Ultra and HP scenarios, where there is an increase in electricity demand.
- **CHP plants** have been adjusted in capacity relative to the number of full load hours of the plants.
- **HPs** have been adjusted in capacity relative to the number of full load hours of the plants.
- **Offshore wind power** capacity has been adjusted to generate the same amount of excess electricity as in the Low scenario.

3. Results

An overview of the analysed scenarios and the main results are presented in Table 5. The results will be further elaborated in the following.

In Figure 4 it is shown how the DH production mix is changing between the scenarios. It can be seen that excess heat production is increasing, due to improved efficiencies, and at the same time CHP and HP production is decreasing as a consequence of this. It can also be seen that the surplus production (the production above the DH supply markers) is increasing with reduced temperatures, which is caused by the increase of inflexible heat production in the low heating season from waste, excess heat, geothermal and solar thermal heat production.

The surplus heat will materialise in a reduced supply of excess heat from industries or cooling via sea water, cooling tower or similar. The increasing surplus heat may indicate a potential for optimisation of the heat

Table 5: Overview of central scenario parameters and results.

	2035					2050				
	Save	Ret	Low	Ultra	HP	Save	Ret	Low	Ultra	HP
Temperature set [°C]	80/40	80/25	55/25	45/25	35/20	80/40	80/25	55/25	45/25	35/20
Additional DHW preparation method	–	–	–	Direct elec.	Booster HP	–	–	–	Direct elec.	Booster HP
Electricity consumption in DHW preparation [TWh]	0	0	0	0.5	0.6	0	0	0	0.6	0.7
Grid loss share [%]	16.5	15.8	14.1	13.2	12.3	14.7	14.1	12.4	11.4	10.5
Total DH Supply [TWh]	30.2	29.9	29.4	28.4	28.9	26.5	26.3	25.8	24.9	25.5
Total energy system costs [B€]	13.27	13.25	13.23	13.25	13.36	13.93	13.88	13.84	13.86	13.96
– Reduction in energy system costs [M€]	–	19	46	27	–88	–	53	98	76	–25
Total PES [TWh]	138.94	138.76	138.17	138.38	138.18	133.59	133.33	132.79	133.05	133.64
– Reduction in PES [TWh]	–	0.18	0.77	0.56	0.76	–	0.26	0.80	0.54	–0.05

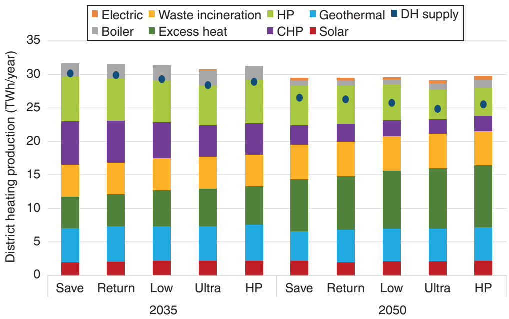

Figure 4: Distribution of district heating production between production units for the five analysed scenarios, in 2035 and 2050

source mix. In the scenarios with low temperatures, the boiler, HP and CHP operates very few hours during the summer, but there is still an overproduction of heat.

The primary energy supply (PES) seen in Figure 5, shows the total changes as a result of all changes in the scenarios. It can be seen that reduction of supply and return temperatures does not influence the PES or fuel consumption significantly. The reduction in PES is in all scenarios less than 0.8 TWh, with the lowest total fuel consumption and PES in the Low scenario compared to the Heat Savings scenario. When the PES of these five scenarios are compared to the DEA Wind scenario, it can be seen that a significant saving is obtained. This is due to the applied measures in the IDA

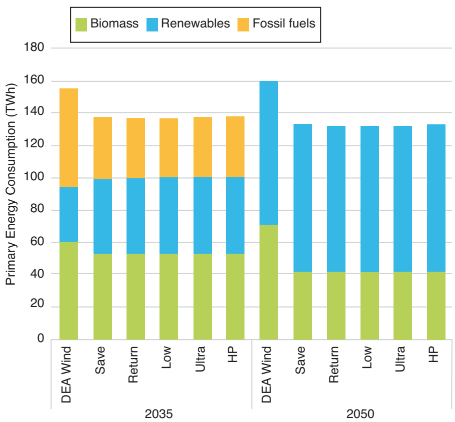

Figure 5: Primary energy supplyin the five analysed scenarios and the DEA Wind Scenario, for 2035 and 2050, divided on biomass, fluctuating renewables and fossil fuels

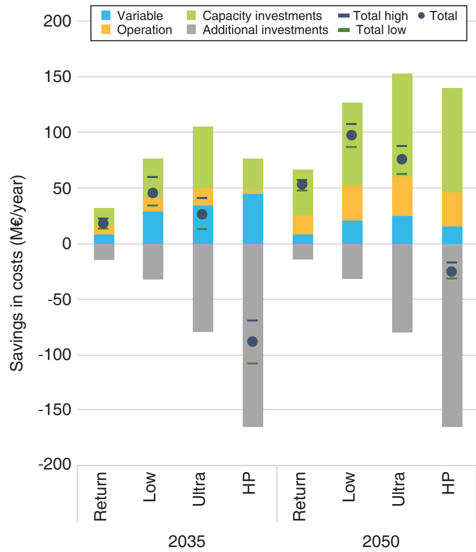

Figure 6: Savings in total costs, divided on Variable costs, Operation and maintenance costs and Investment costs, for the four alternative scenarios relative to the Heat Savings scenario for 2035 and 2050. The sensitivity of the results to high (+50%) and low (-50%) fuel costs is shown compared to the total costs

scenarios that make use of synergies in the integration of energy sectors.

Figure 6 shows the overall economic results of the scenarios where a breakdown of the costs into Variable costs (fuel and variable operation costs), Operation costs (fixed operation costs) and Investment costs. The results show that the scenarios Return, Low and Ultra all are economically feasible compared to the Heat Savings scenario, and that the Low scenario has the lowest costs in both 2035 and 2050. The HP scenario has higher costs than the Heat Savings scenario under the given assumptions. This is mainly due to the investment costs in the individual HPs. As a sensitivity analysis, different fuel cost levels are included in the analysis, as seen in the figure.

4. Discussion and conclusion

The feasibility found in this analysis is based on socioeconomy, but this does not mean that these solutions are also business economically feasible to a DH company. The results should be seen as guidelines to policymakers designing the concrete economic framework for DH development. The results apply on a general level for Denmark, but there will most likely be DH areas that make exceptions from the general conclusions, given specific conditions making them different from a typical case.

4.1. Reduction of temperature set

The results show that reducing temperatures in DH is a feasible strategy on the medium and even more on the longer term, in a transition towards more RE in Denmark. The results indicate that a reduction of return temperatures alone, considering the required investments, is a feasible strategy already today and increasingly with more RE penetration. In the 2050 model the savings are seven times larger than the additional investments. This is at the same time a prerequisite for a substantial reduction of the supply temperature. As the supply temperature is reduced towards the level where electric boosting of the DHW temperature is required, the costs keeps decreasing. From here, through the Ultra and HP scenarios, the costs increase because the additional investments surpass the savings.

4.2. Significance of investment costs

It can be noticed in the results that a reduction in fuel consumption, which might intuitively be the reason to introduce LTDH, is not actually the main benefit on the system level. In all scenarios, except the Return scenario for 2035, the reductions in capacity investments are larger than the variable and operational costs together. As seen in Figure 6, the reductions in capacity investments are increasing until they peak in the Ultra scenario and are lower in the HP scenario, whereas the additional investments have an exponentially increasing tendency through the scenarios. This indicates that a theoretical optimum exists in how low the temperature should be. This is also what can be seen in the trend of the reduction in total cost which peaks in the Low scenario under the given assumptions.

4.3. Electricity for domestic hot water boosting

The two scenarios that use electricity for boosting of the temperature of the DHW show lower reduction in socioeconomic costs, and the Low scenario without electricity use for DHW therefore seems like the most feasible strategy. As mentioned, the investment costs are of great importance to the results. The total socioeconomic savings are 100 and 75 M€ /year for the DH supply systems in Denmark for the Low and Ultra scenarios respectively. The calculated additional investment costs for the electric heaters are 37 M€ /year, and if the costs of these can be reduced by two thirds, the scenarios would be economically on the same level. On the other hand, if the increase in pipe costs is larger than assumed here, the results will tip more in favour of the Low scenario. Because of the high additional costs in the HP scenario and the relatively low increase of the system benefits this is not seen as an option that can be feasible in general. The HP solution might be feasible in concrete cases under the right circumstances, though.

If the costs of the Low and Ultra scenarios would be on the same level, there is still a risk in the Ultra scenario, because the larger investments in the buildings lock the demand to that solution. If these investments are made it is still possible to operate at higher temperatures, but then the investments have been wasted. If an additional unit is added to the DH substation, an electric heater or especially a booster HP, it will also increase the need for maintenance and the risk for errors. The Low scenario is more simple in the sense that it only requires investments that would be feasible anyway and thereby nothing is wasted if the temperatures are not reduced as much or as fast as planned.

4.4. Synergy between LTDH and savings in space heating

One important assumption in this study is the implementation of savings in SH of approximately 45% in existing buildings [17] and new buildings following the building codes with low SH demands as well. In this study, only modest changes in the cost for the DH grid are included because the assumed heat savings enable a reduction in temperature difference between DH supply and return. If no savings in SH are implemented, the temperature difference between supply and return cannot be reduced as much as suggested in this study, and thereby the benefits cannot be achieved either. Alternatively, significantly higher costs in DH grid investments will have to be considered to account for the higher flow needed to cover the demand.

4.5. Sensitivity of the results

The sensitivity of the results to a number of important parameters have been analysed. The costs for the household investments and electricity consumption in DHW boosting are relatively uncertain, because no large-scale implementation have been done, but the values assumed are rather optimistic. Therefore, the costs and electricity consumption will more likely be higher in the Ultra and HP scenarios, making these less feasible compared to the others. In Figure 6, the sensitivity to fuel price changes is presented. These changes in fuel costs can change the relation between the savings in the scenarios, but not the overall results. The same tendency can be seen when altering the applied interest rate and, in the 2035 case, the CO_2-price.

In this study the IDA models of Denmark in 2035 and 2050 are assumed as starting points for the scenario analyses. The pace of the transition towards 100% RE do not influence the conclusions, since the relations between the scenarios are similar in 2035 and 2050. If the development goes in a completely different direction than proposed in the IDA Energy Vision [17], the results may not be representative.

4.6. Conclusion

It can be concluded that it is a feasible strategy to reduce DH temperatures on medium and long term in the development towards a RE system. To reduce the return temperature to about 25 °C requires replacement and adjustment of the building heating systems, but this is feasible to do so, even if the supply temperature is not reduced, with an annual reduction of socioeconomic costs of 50 M€ /year in 2050 for the DH supply system in Denmark. The supply temperature should be reduced as much as possible until electric boosting of DHW becomes necessary, which happens at about 55 °C and gives an annual reduction in socioeconomic costs of about 100 M€ /year. The feasibility on a general level of a further temperature reduction to e.g. 45 °C, taking local temperature boosting of DHW into account, is very questionable and will rely on a very low investment cost in the units to heat the DHW. A solution with micro HPs for temperature boosting seems beyond realistic from an economic perspective, but under the right circumstances in small concrete areas it might be feasible. Before considering electric boosting of temperatures, organisational issuesrelated to trade-offs between benefits for the DH company of reduced temperature and the increased costs for electricity for the consumers have to be solved.

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